The Eemian Baltic Sea hydrography and paleoenvironment based on foraminiferal geochemistry

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Cover Picture: SEM image of *Bulimina marginata.* Photo by Julia Chonewicz and Sha Ni at Lund University 2020

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Abstract: In this thesis, three microfossil records from Anholt (Kattegat), Ristinge (the Danish straits) and Obrzynowo (the southern Baltic- coast) representing the last interglacial Eemian (130- 115 ka B.P) were generated. The geochemistry of benthic foraminifera was investigated to reconstruct the Eemian Baltic Sea hydrography and paleoenvironment. The paleo-environmental proxies were: the trace elements Mg/Ca, Ba/Ca, and Mn/Ca as well as stable oxygen and carbon isotopes ($\delta^{18}O$ and $\delta^{13}C$), coupled with data from previous studies and modern hydrography. The reconstructed bottom water temperature was calculated with species-specific Mg/Ca calibrations and the results indicate generally warmer bottom water temperatures than modern data, albeit for *Elphidium clavatum* and *Bulimina marginata* the results are contradictory and could be a result of seasonal response for shell calcification and incorporation of trace elements. The comparison of the three stations (Anholt, Ristinge and Obrzynowo) show a gradient from marine to gradually more brackish environmental conditions. The oxygen conditions imply a strong stratification and relatively low oxygen levels, except in Ristinge where the transgression of the Danish Straits resulted in relatively ventilated bottom waters as opposed to the other stations. The foraminiferal geochemistry is shown to contribute to quantitative temperature and tentative paleoenvironment reconstructions that can be used as a past analogue for present changes in the environment.

Keywords: trace elements, benthic foraminifera, last interglacial, temperature reconstruction, geochemistry

Supervisor(s): Helena L. Filipsson, Sha Ni

Subject: Quaternary Geology

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Östersjöns hydrografi och miljö under Eem interglacialen, baserat på foraminiferers geokemi

JULIA CHONEWICZ

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Sammanfattning: I den här masteruppsatsen undersöktes geokemin i kalkskalen av bottenlevande foraminiferer från Anholt (Kattegat), Ristinge (Bälthavet) och Obrzynowo (Egentliga Östersjön), för att rekonstruera de hydrografiska förhållanden i Östersjön och paleomiljön under den senaste interglacialen (130 - 115 ka BP). De variabler som analyserades innefattade Mg/Ca, Ba/Ca och Mn/Ca samt stabila syre- och kolisotoper ($\delta^{18}O$ och $\delta^{13}C$) i kombination med data från tidigare studier och modern hydrografi. Den rekonstruerade bottenvattentemperaturen beräknades med hjälp av artspecifika Mg/Ca-kalibreringar och indikerar generellt varmare bottenvattentemperaturer än modern data, däremot är resultaten motstridiga för *Elphidium clavatum* och *Bulimina marginata* och kan vara ett resultat av att olika arter bygger sina skal under olika delar av året. Jämförelsen mellan de tre stationerna visar på en gradvis övergång från marina till mer bräckt vatten. Syreförhållanden tyder på en stark vertikal stratifiering av vattenkolumnen och relativt låga syrehalter, förutom i Ristinge där trangressionen av de Danska sunden resulterade i relativt väl ventilerade bottenvatten i motsats till de andra stationerna. Resultaten från spårelement- och isotopanalyserna från foraminiferer har visat sig kunna bidra till bestämning av absoluta temperaturer och paleomiljörekonstruktioner som kan användas som en analog för nuvarande förändringar i miljön.

Nyckelord: spårelement, bottenlevande foraminiferer, Eem interglacial, temperatur rekonstruktion, geokemi

Handledare: Helena L. Filipsson, Sha Ni.

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1 Introduction

The last interglacial (Eemian; 130-115 ka B.P, Marine Isotope Substage (MIS)5e) was a considerably warmer period with higher global sea levels than in the present (e.g., Knudsen et al. 2012 and references within). During that time period, the Baltic Sea was also characterised by higher salinities (Knudsen et al. 2012) and extensive low oxygen conditions (e.g. Funder & Balic-Zunic 2006). An interesting question in this context is how high the bottom water temperatures (BWT) in the coastal regions of the Baltic Sea were, and also how the salinity varied as well as how severe the low oxygen conditions were? These are some of the questions I ask myself within my Master thesis project. Previous studies have demonstrated environmental conditions (Seidenkrantz 1993a; Knudsen et al. 2011; Knudsen et al. 2012), but quantitatively estimates of actual bottom-water temperatures have not been presented.

The Eemian period was also characterised by a rapid sea-level rise. Marine conditions were present and prevailed throughout most of the period, although a significant freshwater input resulted in brackish conditions later on (Knudsen et al. 2011; Knudsen et al. 2012).

In my master thesis, I have analysed the trace elemental composition and stable oxygen and carbon isotopes in benthic foraminifera, to further detail the paleo-environmental conditions in the Baltic Sea, including the Kattegat. Depending on the conditions in the water column during the life of the foraminifera, different elements will be incorporated into foraminiferal calcite shells (tests). Oceanic conditions reflected in foraminiferal records can, therefore, help with the reconstruction of the previous environment. The analysis was correlated with other proxies, some of which were already available from previous studies (Kristensen et al. 2000; Knudsen et al. 2011; Knudsen et al. 2012). The study is focused on a selected number of species from three stations: Anholt (Kattegat), Dk; Ristinge (Danish Straits), Dk and Obrzynowo (the southern Baltic- coastal region); Pl. The original papers can be found in table 1.

I determined the concentrations of trace elements (Mg/Ca, Ba/Ca, Mn/Ca) as well as oxygen and carbon isotopes from the Obrzynowo station and correlated results with additional proxies from the three stations, respectively. The measurements provided information about the water chemistry during the Late Saalian (MIS6, 135 ka) and the Eemian, with a focus on temperature, salinity and oxygen levels in the bottom waters. Estimates of actual quantitative temperatures of bottom waters in the Baltic coastal region were made, as well as an estimation of variations in salinity and how severe were the oxygen conditions during the last interglacial stage. These reconstructions will put ongoing environmental changes in the Baltic into a larger perspective, helping in environmental predictions that can be based on the paleoenvironmental records.

The aims of the thesis are:

- To contribute with proxy data for the paleoclimatic reconstructions of the Baltic, from the last interglacial (the Eemian stage). The contribution includes the trace element ratios in foraminifera derived from sediment cores of Anholt, Ristinge and Obrzynowo and quantitative temperature reconstructions.
- To show what the foraminiferal geochemistry shows in the reconstruction of environmental conditions.
- Show an estimation of the temperature and oxygen level variations in the bottom waters throughout the Eemian as well as if there is a correlation between Eemian and the present conditions and how it might reflect on increasing low oxygen levels in the modern Baltic Sea.

2 Background

2.1 Baltic Sea: Modern hydrographic setting

The hydrography varies greatly in the Baltic area. Skagerrak is the transition between the North Sea from the northwest and the Kattegat in the south. The system extends to the Danish straits leading the waters to various basins within the Baltic Proper (Figure 1) (Lass & Matthäus 2008). As a part of the Baltic Sea circulation, the Skagerrak is directly connected to the North Sea, with a mean depth of 210 m and deepest part reaching 700 m depths. The various water masses of high salinity originate from North Jutland current and the Atlantic inflow that is even more saline (c. 31-35) and create a cyclonic circulation pattern with input from the Baltic. Low salinity (c. 20) water mass of the Baltic Current follows the Swedish and Norwegian coast transporting surface water from the Baltic and to later join circulation of high salinity waters of the Norwegian Coastal Current (Rodhe 1996).

The Danish Straits consists of the Little Belt, Great Belt (main channel), the Sound (Öresund) (24-53 m, mean depth of 12 m) with the Drogden Sill (8 m depth) and Darss Sill (18 m depth). The sills of Danish Straits then lead to the Arkona Basin (salinity c. 8) (Lass & Matthäus 2008; Leppäranta & Myrberg 2009). Arkona Basin continues into the Bornholm Basin, Gdansk Bay and Gotland Basin into the Baltic Proper. The Danish straits are quite shallow, being mostly below 20 m and borders onto Kattegat from Sjaelland to Skåne (Leppäranta & Myrberg 2009).

The bottom waters in Kattegat are of c. 32 salinity (Groeneveld et al. 2018) and have a mean depth of 23 m and are the passage where a significant water mass mixing prevails, with salinity changes dependant on the variable topography. Areas around the Island of Anholt are deeper where the water depth reaches 100 m, being the deepest in the region. The mixing circulation results in the Kattegat having a pronounced halocline (15-20 m depth) with the Baltic origin water with lower salinity overlaying the denser water (Leppäranta & Myrberg 2009).

The Baltic Sea is landlocked, and the saline inflow gives it a general brackish salinity. The Baltic Sea has a strong permanent stratification and a weak vertical circulation, thus restricting the mixing and resulting in poor ventilation of the bottom water. The two water masses are permanently vertically stratified and separated by a halocline (Leppäranta & Myrberg 2009) and seasonally steered thermocline (Conley et al. 2009). The salinity in the central parts varies from 6-7 in the surface water and deep water from 10-14 (Lass & Matthäus 2008). Generally shallow, the entire Baltic Sea is also relatively small with -392.978 km2 and volume of 21.205 km3, the mean depth is 54 m (Leppäranta & Myrberg 2009). The freshwater influence into the Baltic is dominating due to the input from rivers drainage from the surrounding countries (Lass & Matthäus 2008). The Baltic is thus a positive estuarine system as the precipitation, and the input of freshwater are larger than evaporation (Filipsson et al. 2017).

The climate in the Baltic Sea area is both sub-Arctic and maritime temperate (Leppäranta & Myrberg 2009). The temperature, according to SMHI, is generally 4 to 5^{o}C in the surface water of the Baltic and about 6^{o}C in Kattegat (SMHI 2018). Temperature variability in the Baltic can shift in the energy balance depending on the season, yet the bottom waters vary in lesser grade than the surface waters. Regions with heightened advection due to the influence the saline inflow trough the Danish straits, like the southern parts of the Baltic, vary more in temperature even in the bottom waters. The halocline strongly prevails in the Baltic and is usually at a depth of 15-30 m, during summer due to the river- runoff that benefits the stratification of water masses (Lass & Matthäus 2008).

Due to the above mentioned extensive input of freshwater into the Baltic, the nutrient enrichment has increased, resulting in eutrophication in coastal areas (Diaz & Rosenberg 2008). The large input of nutrients from freshwater runoff affects the components like biochemical cycles of N, P and O2 and the production of organic matter increases. The nutrient influx results in an increase of organic productivity that, in turn, causes the decrease of oxygen levels, due to the remineralisation of oxygen (Matthäus et al. 2008). This process of oxygen depletion often leads to hypoxia that is defined as the levels of dissolved oxygen falling below ≤2 ml/l of O2. Due to that response in the bottom water oxygen levels, increasingly hypoxic bottom water conditions have been recorded in Kattegat and the Baltic since the 1960s. (Diaz & Rosenberg 2008). The strong vertical stratification also amplifies the depletion of oxygen (Diaz & Rosenberg 2008). The salinity stratification is a strong limitation for vertical movements of water and results in anoxic bottom water conditions, and generally causes low oxygen trends in the Baltic Sea (Leppäranta & Myrberg 2009). Similarly, to other continental marine environments other than the Baltic (e.g. The south-west Atlantic, eastern Pacific and Bay of Bengal) the combination of these factors can lead to a broadly occurring hypoxia (Diaz & Rosenberg 2008). The observed strengthening of the stratification and lack of ventilation due to limited deep water exchange in the Baltic has been recently amplified by anthropogenic activity on the water discharge into the Baltic, a factor in the strengthening of eutrophication (Conley et al. 2011; Groeneveld et al. 2018).

2.2 Foraminifera

Foraminifera are microorganisms often with a calcareous test (Boersma 1998). These microorganisms are classed under the Protists phylum and have enclosed shells that consist of chambers (Murray 2006). These protozoans can be broadly classed in benthic foraminifera, which have evolved during the Cambrian, and planktonic foraminifera species which have existed since the Mesozoic. They provide a wide variety of microfossils and are currently inhabiting the world's oceans in both shallow and deep water (Boersma 1998).

I focused on four species of benthic foraminifera in this thesis. *Bulimina marginata* d'Orbigny is an opportunistic taxa that thrives in sediments with a large organic content as well as oxygen-poor conditions (Hess & Jorissen 2009; Charrieau et al. 2018). *Hyalinea balthica* (Schroeter) is a species that thrive in colder temperatures (although not Arctic) and can be found in abundance in the North Atlantic (Murray 2006; Rosenthal et al. 2011). The species prefers shallows sediment levels but is also present in the deeper successions with where lack of oxygen occurs similarity to *B. marginata* (Hess & Jorissen 2009; Rosenthal et al. 2011). *Ammonia batava* (Hofker) is an opportunistic species thriving in brackish waters, and they have the ability to adapt well to large environmental variation (Murray & Alve 1999; Toyofuku et al. 2011 and references within). *Ammonia batava* was previously classed as *A. beccarii* but have been recently reassigned (e.g. Groeneveld et al. 2018; Bird et al. 2020, personal communication Karen Luise Knudsen 2019) and was in this thesis called *A. batava* for the data presented. *Elphidium clavatum* Cushman is a common species of foraminifera, widespread although mainly distributed in high latitudes like the Arctic. The species is also tolerant of restrictive environments which characteristics like, oxygen-poor conditions that can be found in the Baltic (Conradsen 1993; Darling et al. 2016 and references within).

The distribution of benthic foraminifera is believed to depend on temperature, water depth and hydrostatic pressure that has an impact on chemical processes like gas solubility and hence the formation of calcium carbonate of the foraminiferal test (Boersma 1998). The different species of foraminifera need to be considered with the account to their ecology, as diverse species have different sensitivity that might affect their vitality (temperature sensitivity, metabolism, ontogeny) in an environment and reflect that in the geochemistry (Boersma 1998; Rosenthal et al. 2011; Groeneveld & Filipsson 2013; Grunert et al. 2018).

2.3 Trace elements

The usage of trace elements as an indicator of past environmental conditions is growing in interest and usage of them are increasing. Trace elements are an important tool for palaeoceanography and, e.g. Mg/Ca can be used to reconstruct temperature. The composition of trace elements in seawater (i.e. biochemical cycling of nutrient- like, conservative and particle-reactive elements) can differ depending on the depth and the amount of source water (marine input and river discharge) as well as different mixing patterns. The difference in hydrographic conditions that affect the elements can also influence the biological and physical aspects of foraminiferal calcification and thus reflecting in their tests where the elements have been preserved (Elderfield et al. 1996; Lea 1999). As the elements are incorporated in the foraminifera tests, the variability in paleotemperatures can be shown by Mg/Ca and $\delta^{18}O$ stable isotopes (Nürnberg et al. 1996). Distinctive for coastal regions with a tendency to vary in temperature and salinity like the Baltic, is that it reflects on both the Mg/Ca and $\delta^{18}O$ ratio of the foraminifera, although the salinity parameter has less impact on these aspects as opposed to open marine environments (Nürnberg et al. 1996; Toyofuku et al. 2011).

There are both exponential and linear relationships of Mg and temperature which with calibrations (core-top and culture studies) for arctic species will be used for reconstructing of paleotemperature (Martin & Lea 2002; Kristjánsdóttir et al. 2007; Filipsson et al. 2010).

Mg/Ca is used here as a temperature proxy, due to the relationship between Mg content and the temperature, that is reflected by the concentration of the elements incorporated in the test (Elderfield et al. 1996; Nürnberg et al. 1996; Lea 1999). Mg is a conservative element meaning it remains relatively stable in the system, and thus changes in their concentrations reflect on changes in water conditions that might have occurred and influenced the incorporation of the element (Lea 1999). Water with higher temperature results in a larger the precipitation of Mg in carbonate shells, yielding high values for environments that are warmer, like shelves, the usual range is 0.5 to 10 mmol/mol (Elderfield et al. 1996; Lea 1999).

Ba/Ca ratio is used as a salinity proxy due to it being strongly coupled to river runoff. The Baltic being an enclosed basin is a good environment for assessing the potential of Ba/Ca as a salinity proxy, (Bahr et al. 2013; Groeneveld et al. 2018 and references within). Manganese (Mn) is a redox sensitive element that can be found incorporated in the foraminiferal tests during hypoxic conditions (Barker et al. 2003) and depends thus on the grade of oxidation. Mn is present as Mn oxides and Mn oxyhydroxide in oxygen-rich conditions and as Mn^{2+} under hypoxia. To use Mn^{2+} as a proxy for the low oxygen conditions, it is important to distinguish the oxidised coating and the precipitated element of the test (Tribovillard et al. 2006; Groeneveld & Filipsson 2013). A potential Mn-oxide coating is possibly removed in a reductive step of the foraminiferal cleaning (Barker et al. 2003).

It is important to note that different species of foraminifera might have a different composition of Mg/Ca due to their different habitat and other factors like biological processes impacting the calcification of the test (Elderfield et al. 1996; Lea 1999).

2.4 Sampling locations

Three localities are discussed in this paper (Figure 1, Table 1). The first one is situated on the north-western side of the island of Anholt, Kattegat. The drilling took place in spring 1990, with three borings were made, in this study only the boring Anholt III are considered. Approximately 7.8 m of the drilled core represents the Saalian and Eemian sediments that are of interest in this paper (Seidenkrantz 1993a).

The second locality, Ristinge, is situated in Langeland, southern Denmark. The sediments of importance in this paper are the *Cyprina* Clay, described in Kristensen et al. 2000 (Table 1). The age model for the sediments in Ristinge sequence is originally from Kristensen et al. (2000), and further correlations follow in Knudsen et al. (2011). The sequence is enabled to be correlated with Bispingen sequence that has been previously used as a base sequence for north-western Europe (Kristensen et al. 2000: Knudsen et al. 2011).

The third station is located in Obrzynowo, northern Poland (Table 1). The core was first described by Makowska (1997). Here, pollen data correlations with bottom water assemblages have been made with this core and time zonation was also concluded (Knudsen et al. 2012). Similarly, to Ristinge, here the pollen zone boundaries of the sequence have been compared to Bispingen time scale. The age scale is given in years after the Saalian/Eemian boundary, a floating time scale, where regional pollen zones with their corresponding ages were applied in the section,

Table 1. The table presents the stations, the type of published analyses and references.

Station	**Analysis**	**Source**
Anholt	Amino acid dated ages Foraminiferal assemblages and stable isotopes from benthic foraminifera Eemian environments and variability in Danish stations	(Knudsen & Sejrup 1988) (Seidenkrantz 1993a) (Seidenkrantz 1993b; Seidenkrantz & Knudsen 1994) (Lykke-Andersen et al. 1993) (Seidenkrantz et al. 2000)
Ristinge	Paleo-vegetation, foraminiferal - and ostracod correlations, age model Reconstruction of stable isotope data and further correlation against a floating chronology	(Kristensen et al. 2000) (Knudsen et al. 2011)
Obrzynowo	Pollen chronology levels and hydrography Correlation of pollen and bottom water assemblages of both foraminifera, diatoms and ostracods against a floating chronology	(Head et al. 2005) (Knudsen et al. 2012)

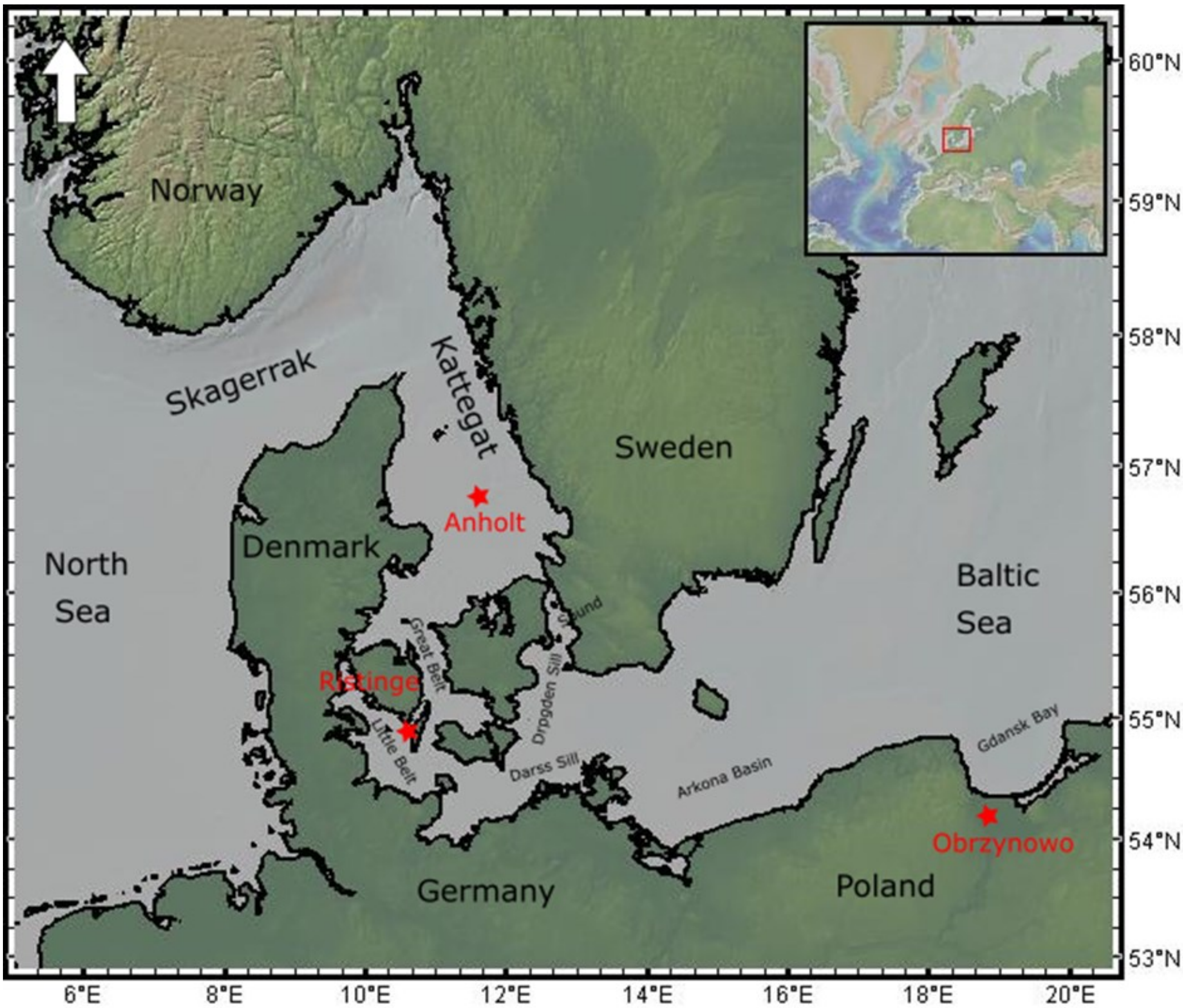

Figure 1. A map of the southwestern Baltic Sea area where all three stations are marked with a red symbol (base map source, Geomapapp).

starting with 300 years after the beginning of the Eemian. Following at 11.85m the next zone has been placed for c. 750 years, zone E4 is at 108.4m and continues until c. 7000 years at the end (Knudsen et al. 2012).

2.5 Stable oxygen and carbon isotopes

Stable O and C isotopes are another proxy of importance for paleorecord interpretations. Isotopes of different elements are incorporated in the foraminiferal tests under their growth from their surrounding environment. The oxygen and carbon isotopes can be used for estimation of temperature, salinity and the specific water conditions. Stable isotopes possess a different atomic mass of the same element due to the difference in the number of neutrons between the isotopes. Two variants of significant stable isotopes for this thesis is oxygen (^{18}O & ^{16}O) and carbon (^{12}C &^{13}C) (Hillaire-Marcel & Ravelo 2007; Bokhari Friberg 2015). The isotopic values are measured in Vienna Pee Dee Belemnite (VPDB), showing the ratio of isotope variants, presented as delta (δ) (Katz et al. 2010). A positive δ implies a higher ratio of the heavier isotope, as the negative values show a lower proportion of heavier isotopes (Hillaire-Marcel & Ravelo 2007).

3 Methods

3.1 Sample preparation

The laboratory procedures were conducted at the Department of Geology at Lund University, with the guidance of Sha Ni and Helena Filipsson. The practical work was carried out between November of 2019 and January 2020. The samples used for the measurements come from earlier studies (Table 1). Depending on the species the hardness of test varied, but overall, the specimens were well-preserved with few cracks although some miss colouring and contamination in the tests prevailed in some depths. The specimens collected for analysis for Anholt were *Bulimina marginata* (20 specimens) and *Hyalinea balthica* (20), for Ristinge and Obrzynowo *Ammonia batava* (20) and *Elphidium clavatum* (100). For the isotope measurements, the same amount of specimens was picked. Prior to the practical work, the foraminiferal assemblage data from the Anholt site was also transferred from paper copies into a digital form.

3.2 Foraminifera picking

The samples have previously been prepared and wetsieved (references in Table 1). In order to use a specific size range for analysis, all samples were dried sieved through four or fewer sieves with different fractions, depending on the state of the sample. The sieves were 125-250, 250-355, 355-500 and >500µm fractions, in some cases, the 500µm was excluded. The fractions of sieved samples from each station were examined under a light microscope for specific species of foraminifera. The foraminifera were collected on slides separating the fractions and species. No other than the selected species were picked for the stations. The foraminifera were thereafter carefully crushed between two glass slides.

Images were obtained using the Scanning Electron Microscope (SEM), model Tescan Mira3 Resolution Schottky field emission-scanning electron microscope (FE-SEM) at Lund University. The specimens were mounted onto a carbon tape and coated with 6nm platinum and palladium. The high resolution was acquired with backscattering.

3.3 Foraminiferal Mg/Ca cleaning procedure

The cleaning followed the standard procedure in Barker et al. (2003) modified by Groeneveld. The procedure was conducted at the University of Bremen by myself with support and supervision from Jeroen Groeneveld.

Preparation for each sample was conducted with the following steps: the initial cleaning for clay removal, entails assembling racks of 16 samples (15 samples and one blank) and repeatedly submerging them in a sonicator bath of lowest intensity ~10% and rinsed alternatingly with *Seralpur* (distilled water) and methanol. For the removal of organic material, the oxidative cleaning is involving H_2O_2 and NaOH solution. The reductive cleaning removes metal coating and uses a buffer solution of Na acetate, (NH_2OH) HCl (hydroxylamine hydrochloride) and a 70ºC bath.

The washed samples were transferred to new vials. The acid leaching step followed by adding 0.001 M distilled HNO_3 to the samples and proceeded with rinsing, here the volume of the sample was estimated before the rest of the solution was removed. Cleaned beakers were used for the step of acidifying for analysis with adding 0.075 M HNO_3 and exposing the samples for sonication bath. The samples were placed in a centrifuge for 10 min on 60rpm to settle the undissolved particles so that separation of the solution would be possible. According to the previously estimated volume for each sample, they are later transferred to beakers with sufficient amounts of *Seralpur*. After these steps, the samples are ready for the trace elemental measurements.

3.4 Trace element analysis

The trace element analysis was conducted at the MARUM- Center of Marine Environmental Sciences, University of Bremen, Germany. The machine used for the analysis was an Inductivity Coupled Plasma Optical Emission Spectrometry (ICP- OES), Agilent Technologies, 700 Series, also using micro-nebuliser and an autosampler ASX-520 Cetac. The trace elements of Ba, Mg and Mn, were plotted against depth in Grapher.

For Mg/Ca temperature calibrations were applied on the Mg measurements and later plotted against depth in Grapher. The Mg/Ca-temperature calibrations employed in this paper are presented in Table 2. Calibration for *E. clavatum* is replaced with *Melonis barleeanus*, for a semi-quantitative result derived from modern arctic foraminifera (Kristjánsdóttir et al. 2007). Another calibration for *E. clavatum* has been established by Barrientos et al. (2018), but the temperature span for that calibration only covers -1.82 to 0.3 °C.

The exponential calibrations follow a basic function for temperature calculation described in Wit et al. 2012; Mg/Ca = a · $e^{(b_*T)}$. The temperature is given in Celsius degrees, and the variables are specific for each species. The variable "a" stands for ratio Mg/Ca at 0 degrees and "b" shows the increasing temperature (Wit et al. 2012). For equation 2, 3 and 4, a temperature envelope could be calculated with the ± values.

Here broad temperature ranges were used, for *B. marginata,* the temperature range was 3-13ºC based on Grunert et al. (2018) calibration. For *H. balthica,* the calibration temperature range is ~4°C–12°C (Rosenthal et al. 2011). *Ammonia batava* temperature range that the applied for the calibration is from 10-27ºC (Toyofuku et al. 2011) and for *E. clavatum* where *M. barleeanus* was used the range is ≤ 4ºC (0-7ºC) (Kristjánsdóttir et al. 2007).

The values were statistically tested for signifi-

Table 2. The assembled temperature calibration calculations used on specific species. The originals calculations have been provided as well as the ones used in temperature calculations presented in this thesis.

Source	Species	Expression	Equation	T (ºC)
Toyofuku et al. (2011)	*Ammonia beccarii* for *Ammonia batava*	T= 18.8**ln* (1.74* Mg/Ca)	1	T=18.8**ln* (1.74* Mg/Ca)
Kristjánsdóttir et al. (2007)	*Elphidium clavatum* is replaced with *Melonis barlee-*	Mg/Ca = 0.658 (± 0.07) * exp 0.137 (± 0.020) * T	2	T= *ln* (Mg/Ca /0.658) /0.137
Grunert et	*Bulimina mar-*	Mg/Ca = 0.114 (±0.012) T +	3	T= (Mg/Ca - 0.938) /0.114
Rosenthal	*Hyalinea balthi-*	Mg/Ca = (0.520 ±0.036)	4	T= (Mg/Ca+0.307) /0.520

cant trends, with a Mann- Kendall test in the PAST software. A p-value of a tested trend lesser than 0.05 (Agarwal 2006) rendered as a significant trend with either positive or negative direction.

3.5 Stable oxygen and carbon isotope analysis

The $\delta^{18}O$ and $\delta^{13}C$ isotope measurements were performed on 30 samples from the Obrzynowo, Poland site. The instruments used were a Thermo Fisher Scientific 253plus gas isotope ratio mass spectrometer (IRMS) with Kiel IV automated carbonate preparation device at MARUM, Bremen University, Germany. The samples analysed for stable isotopes were of 125-250 µm fraction and consisted of individual specimens ranging between an amount of 6-13 for *A. batava* and 19-21 for *E. clavatum*. The standard deviation (S.D.) of house standard (Solnhofen limestone) over the measurement period was 0.03‰ for $\delta^{13}C$ and 0.07‰ for $\delta^{18}O$. The notation for measured results is given in V-PDB.

3.6 Modern hydrographic measurements of the locations

Instrumental data from the three stations (proximity) were acquired from the Baltic Nest Institute, Stockholm University Baltic Sea Centre. The data provides information about the modern hydrographic settings of the stations discussed in this thesis. The measurements were derived from the stretched areas (Figure 2) in the vicinity to the locations, and the data used for the figures range from 1949-2019, recording 70 years of temperature, salinity, and total oxygen sampling. For this thesis, a depth range has been chosen for each station, indicating the bottom water depth corresponding to that in the Eemian in the same area. The mean depth of Anholt is 30.1 m (20.8 to 40 m), Ristinge is 21.8 m (15 to 29.5 m) and Obrzynowo is 30.1 m (20.8 to 40 m). The instrumental data has been plotted in box and whiskers graphs with month coordinated data showing a seasonal spread of 70 years.

3.7 Age model for Eemian

The correlation of time scale seen for the figures was based on Funder et al. (2002) and the samples original references (table 1). Miettinen et al. (2014) enabled a correlation between 750 years after the beginning of the interglacial corresponding to c. 130 ka B.P. which is also connected to the high-level stand. The high-level stand of the eastern Baltic Sea had a duration of 6000 years (Miettinen et al. 2014). Studies from the Greenland ice volume in Rohling et al. (2019) indicate the average sea level during the last interglacial to have been higher than in the present and during 129-125 ka B.P. sea level high stand occurred, whereas 125- 124 ka B.P. a sea level drop was recorded with a low stand during that time. The Anholt station was originally assigned seven zones, three of those were applied in this thesis (E, F and G). Zone E is believed to be the Saalian/Eemian boundary, marked with isotope stage 6, at c.130 ka B.P. Zone F, with isotope event 5.53 at c 129-124 ka B.P.. Zone G lies between 5.53 and 5.51 estimated the age between 124 ka B.P. and 118 ka B.P. This timespan represents the transition from isotope stage 6, late Saalian (135 ka B.P.) to the isotope substage 5e, assigned to the Eemian interglacial (Martinson et al. 1987; Seidenkrantz 1993a). Unfortunately, the resolution of samples investigated in this thesis was not reaching that Saalian stage and is, therefore, outside the scope of this thesis. This correlation of the two stations (Ristinge and Obrzynowo) can be connected to the bottom part of the succession in Anholt as there is a correspondence of 130 ka B.P to 750 years on the floating scale. It is assumed that 124 ka B.P. occurred 6000 years later (Miettinen et al. 2014).

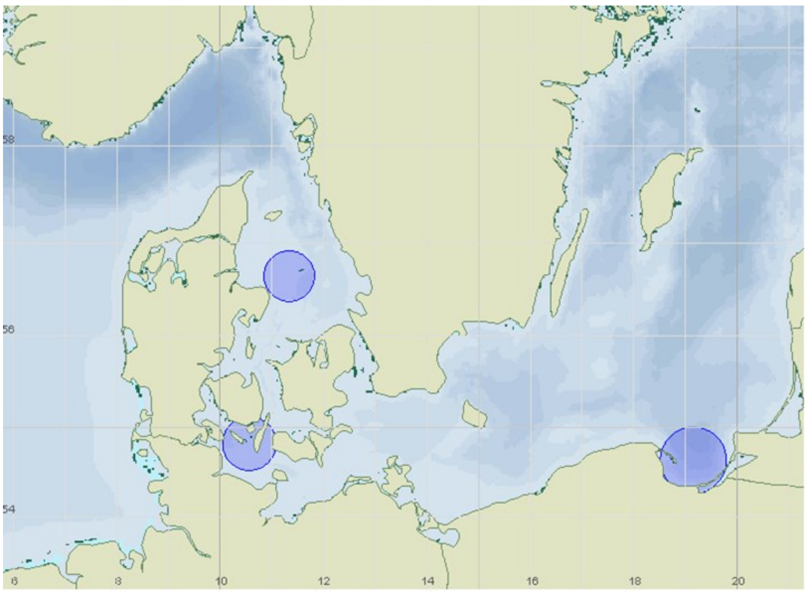

Figure 2: A map derived from Baltic Nest Institute, Stockholm University Baltic Sea Centre. The marked circles represent the area used for acquiring instrumental hydrographic measurements for Anholt, Ristinge and Obrzynowo between 1949 and 2019.

4 Results

4.1 Introduction to the trace elemental analysis and other results

Here I present the results of the trace elemental analysis derived from foraminifera sampled at the three stations. The outline is as follows, starting with trace elemental data with representative SEM images of foraminifera, the quantitative temperature reconstruction and modern-day seasonal hydrography.

From the three sites: 60 samples in Anholt, 107 in Ristinge and 77 in Obrzynowo were successfully analysed (Appendix 1). A few samples were discarded from the analysis, as they did not reach the optimum weight range, meaning they did not contain a sufficient amount of material in the sample that consequently rendered biased results.

Duplicate samples were averaged, and standard deviations were calculated, showing an offset that can be applied to the other samples. All trends derived from the data have been tested using the Mann-Kendall test, for trend direction and significance (Table 3). It should also be noted that the data only resulted in six significant trends out of the 27 species-specific results.

Table 3. This table presents the results of the Mann-Kendall test of trends seen in the data. Only the significant trends are included. The s- values indicate the trends and p- values shows the significance if < 0.05.

Locality and species	Mg/Ca	Ba/Ca	Temp.	$\delta^{18}O$
Anholt, ***B. marginata***		S:33 p: 0.0011		
Ristinge, ***A. batava***	S:98 p: 0.00164	S:-142 p: 4.77 $*10^{-06}$	S:95 p: 0.00100	
Obrzynowo, ***A. batava***		S:33 p: 0.0011		
Obrzynowo, ***E. clavatum***				S:-40 p: 0.032496

4.2 Anholt, Kattegat

SEM plate for Anholt

A plate was composed for the Anholt station (Figure 3) representing the foraminiferal species that are considered for trace elemental analysis.

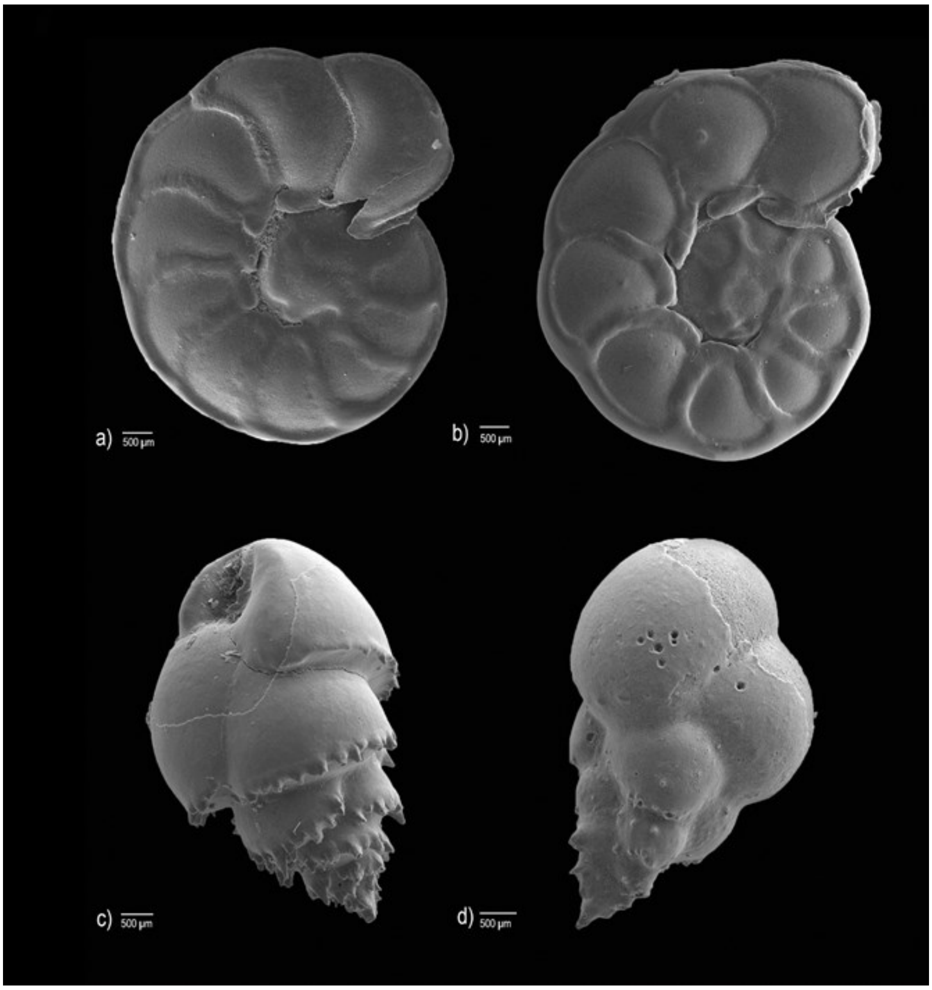

Figure 3: Foraminifera species from Anholt, a-b) represents *Hyalinea balthica* and c-d) *Bulimina marginata,* acquired using the SEM at Lund University.

4.2.1 Trace elemental data

4.2.1.1 Mg/Ca and paleotemperature

The Mg/Ca (Figure 4) ranged between 1.67- 2.07 mmol/mol for *B. marginata* and 3.81- 4.53 mmol/mol for *H. balthica*, a considerable difference can be seen between the two since *H. balthica* had higher ratios than *B. marginata* (Table 3, Appendix 1).

The calculated temperature range in Anholt was between 6.4-9.9ºC, with an average temperature of 8.2ºC for *B. marginata*. *Hyalinea balthica* temperatures range between 7.9-9.3ºC with an average of 8.5ºC (Figure 13a). No significant trends were recorded.

4.2.1.1 Ba/Ca and Mn/Ca

The Ba/Ca (Figure 4) ranged between 0.93-3.93 µmol/mol for *B. marginata*, 5.35- 10.24 µmol/mol for *H. balthica* and the values show a positive trend for *B. marginata*, whereas there was no significant trend for *H. balthica* (Table 3, Appendix 1).

The Mn/Ca (Figure 4) ranged between 0.063- 0.10 mmol/mol for *B. marginata* and 0.35- 0.66 mmol/mol for *H. balthica*. *Hyalinea balthica* showed no significant trends for this element, but it follows a "zig-zag" pattern of oscillations in contrast to the "straighter" pattern of *B. marginata* (Appendix 1).

4.2.2 Modern hydrography in Anholt

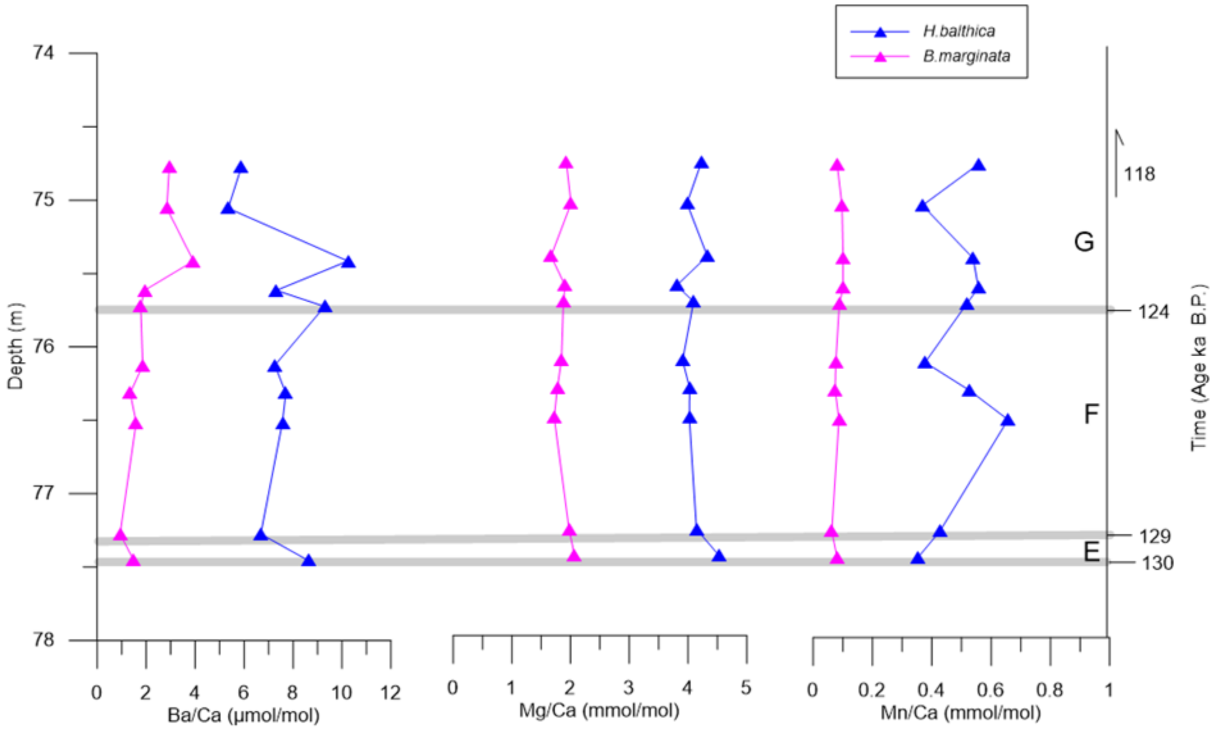

Figure 4. Trace element measurements for Anholt. The elements presented in the figure are Ba/Ca, Mg/Ca and Mn/Ca. The timescale has been correlated according to Seidenkrantz (1993a), in thousands years B.P.

The modern hydrographic settings for the Anholt area is shown in figure 5. The modern data illustrates the seasonal variability in hydrographic parameters at a depth of 30.1 m, closely corresponding to the assumed bottom water depth during the Eemian. Temperatures were distinctively higher (ranged between 5.4 and 13.3ºC) during the spring-summer months (April-September), and lower variability during the autumn-winter period (ranging from 5.3 to 12.3ºC in October- March) (Figure 5a). The salinity in Anholt displayed a considerable variability between 29.6 to 32.7 (Figure 5b). The oxygen levels showed a similar pattern, with the lowest dissolved oxygen [O2] (~4.6 ml/l) during August- November (Figure 5c). It is important to note that Anholt had considerably fewer data points than Ristinge and Obrzynowo. The modern-day oxygen concentrations in Anholt have not reached hypoxic conditions.

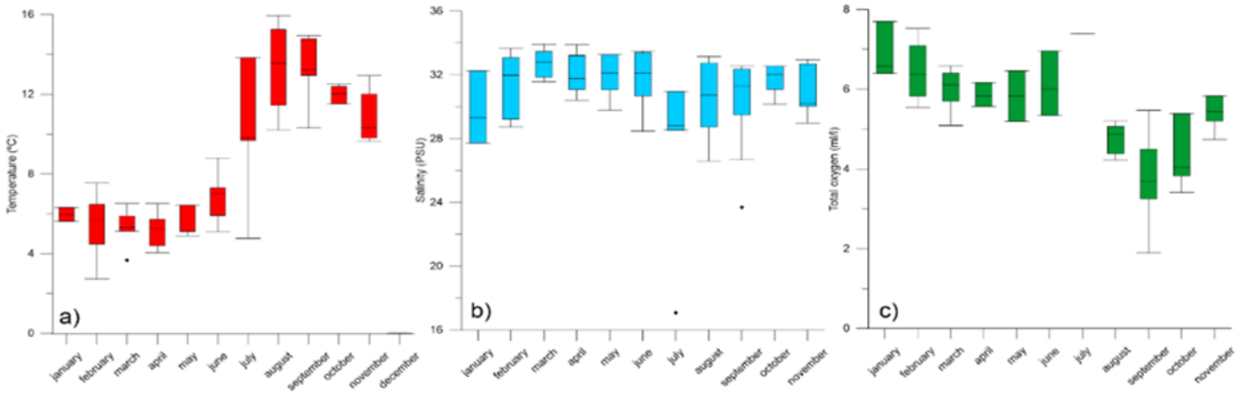

Figure 5. The modern hydrographic settings for Anholt shows the seasonal variability between 1949 and 2019. The graph a-c represents temperature (ºC), salinity (PSU) and dissolved oxygen concentration (ml/l), respectively. For Anholt, no data was recorded in December. The data was acquired from the Baltic Nest Institute, Stockholm University Baltic Sea Centre, 2020.

4.3 Ristinge, the Danish Straits

SEM plate for Ristinge

Two species (*A. batava* and *E. clavata*) were analysed at the Ristinge station in the Danish Straits (Figure 6).

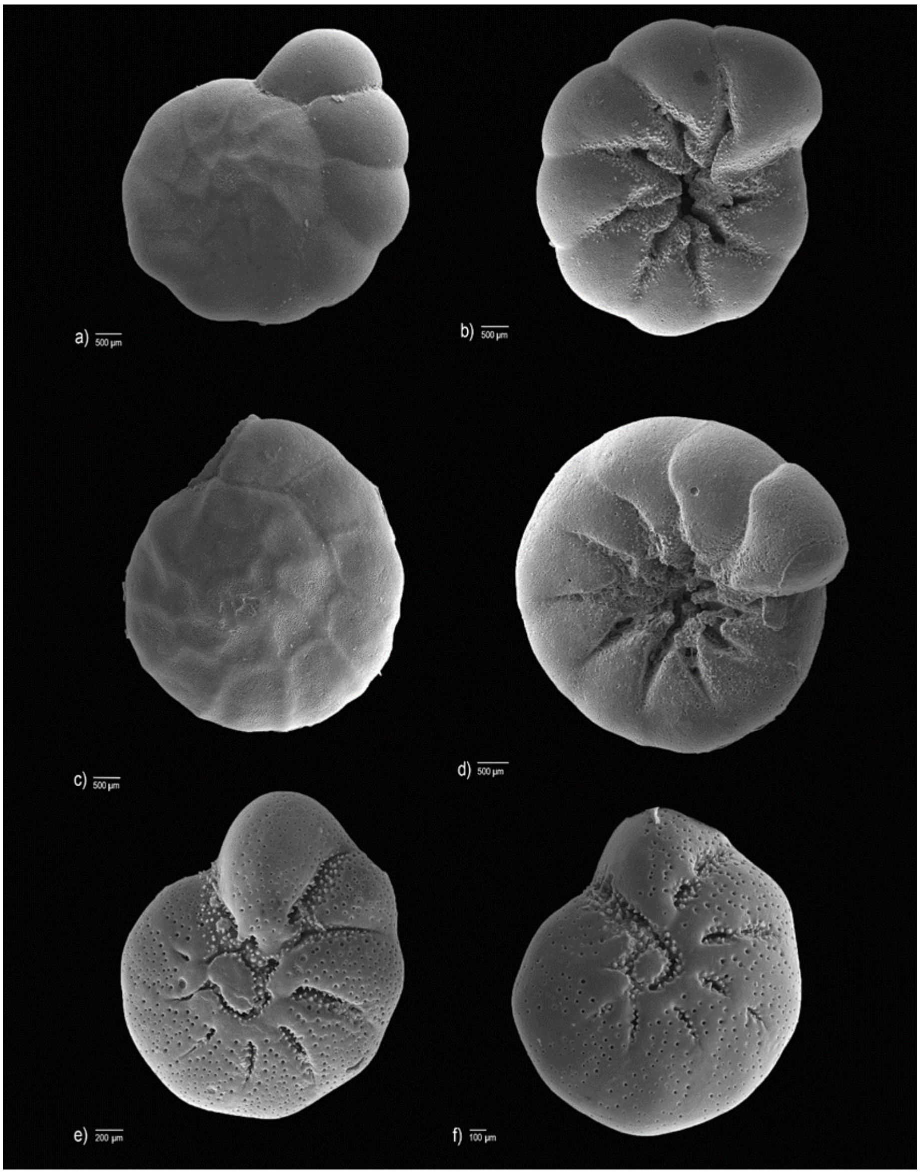

Figure 6: Foraminifera species from Ristinge, a-b) and c-d) represents *A. batava* with a view on the spiral and umbilical side, respectively. Pictures e-f) show E. clavatum, acquired by SEM at Lund University.

4.3.1 Trace elemental data

4.3.1.1 Mg/Ca and paleotemperature

The values for both species were within a close range of each other (Figure 7). Mg/Ca ranged between 0.36- 1.23 mmol/mol for *A. batava* and 0.93-1.25 mmol/mol for *E. clavatum*. There is a significant positive trend for *A. batava* through the whole succession although at 33 and 136 cm a divergence occurs. One sample (D2 at 18cm) was excluded from further analyses due to an insufficient amount of material in the sample (Table 3, Appendix 1).

In Ristinge the calculated temperatures for *A. batava* ranged from 4.0 to 12.7ºC with an average of 8.9ºC, and for E. clavatum, the temperature ranged from 2.4-7.1ºC with an average of 4.1ºC. The temperatures in the samples from Ristinge showed a positive trend for *A. batava* and no trend for *E. clavatum.* Notable is the temperatures difference between the two species. The samples in Ristinge have a few outliers at 166, 136 and 54 cm depth. The outlier sample C13 (depth 136 cm, with a temperature of 7.9ºC) has been discarded from the figures but is included in the table. Similarly, sample D2 (with a temperature of 8.3ºC) has been excluded from analysis (Table 3, Appendix 1). The exclusion is due to them not reaching the optimal range of Ca concentration (<5-10 ppm) of the analysis.

4.3.1.2 Ba/Ca and Mn/Ca

The Ba/Ca (Figure 7) ranged between 4.77- 18.55 µmol/mol for *A. batava*, showing a significant decreasing trend which was seen between 6.70- 19.04 µmol/mol for *E. clavatum* (Table 3, Appendix 1). The Mn/Ca (Figure 7) ranged between 0.23-0.45 mmol/mol for *A. batava* and 0.08-0.24 mmol/mol for *E. clavatum* and showed no significant trends (Appendix 1)

4.3.2 Modern hydrography in Ristinge

The modern hydrographic settings for the Ristinge area are shown in figure 8. The data derived at an average water depth of 21.8 m which corresponds to the assumed water depth during the Eemian at this location. There was a marked seasonality in the temperature (ranging between 4.5 to 13.4ºC) and the dissolved oxygen concentration, ranging between 3.3 and 7.8ml/l. The plotted salinity is substantially analogous,

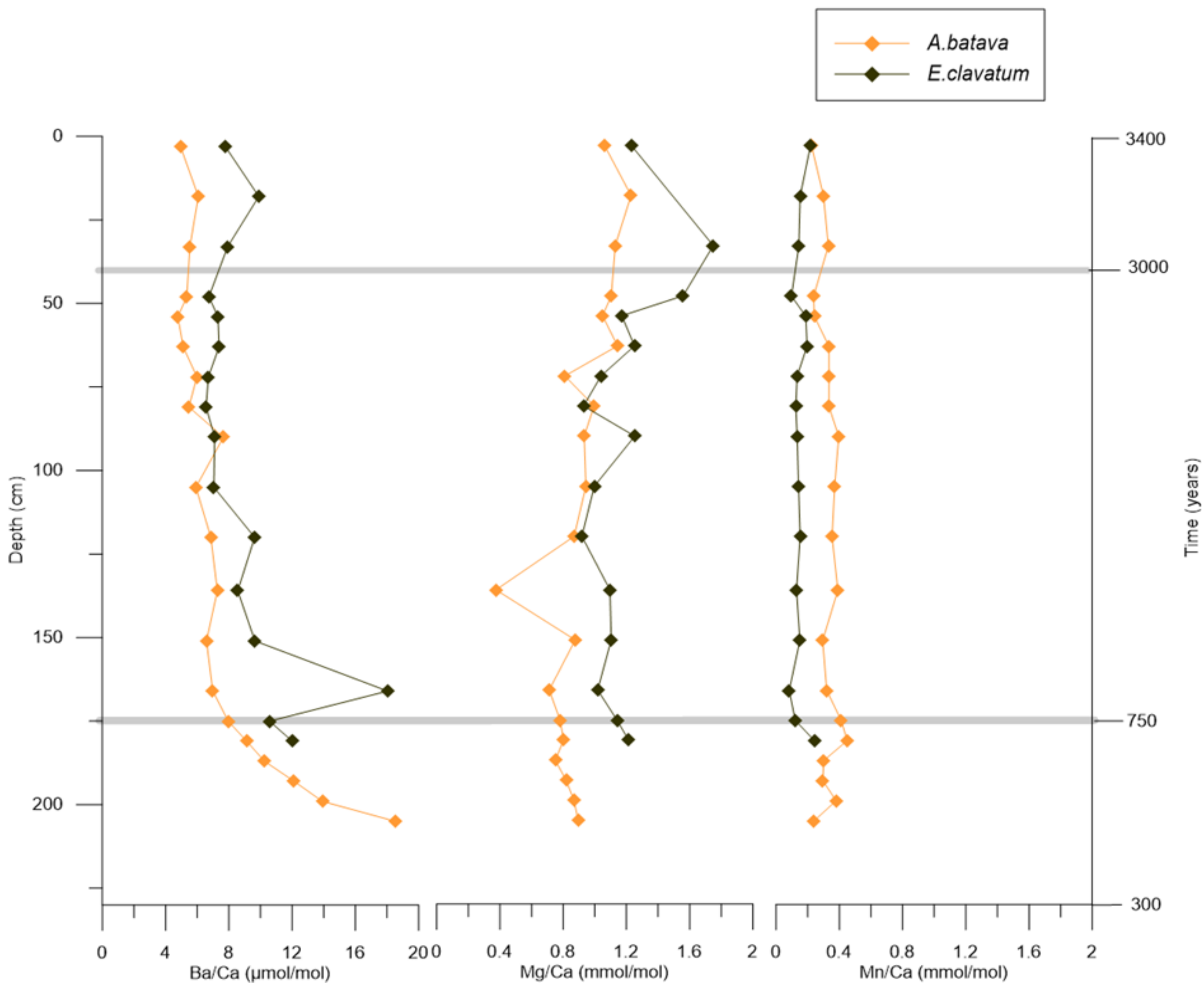

Figure 7. Trace element measurements for Ristinge. The elements presented in the figure are Ba/Ca, Mg/Ca, and Mn/Ca. The timescale follows Knudsen et al. (2011), years after the commencement of the Eemian.

staying within the range of 19.1-21.8 (Figure 8b). The oxygen levels displayed a similar pattern, although it was also the opposite of the temperature (Figure 8c). In this station, oxygen levels were closer to reach hypoxic conditions.

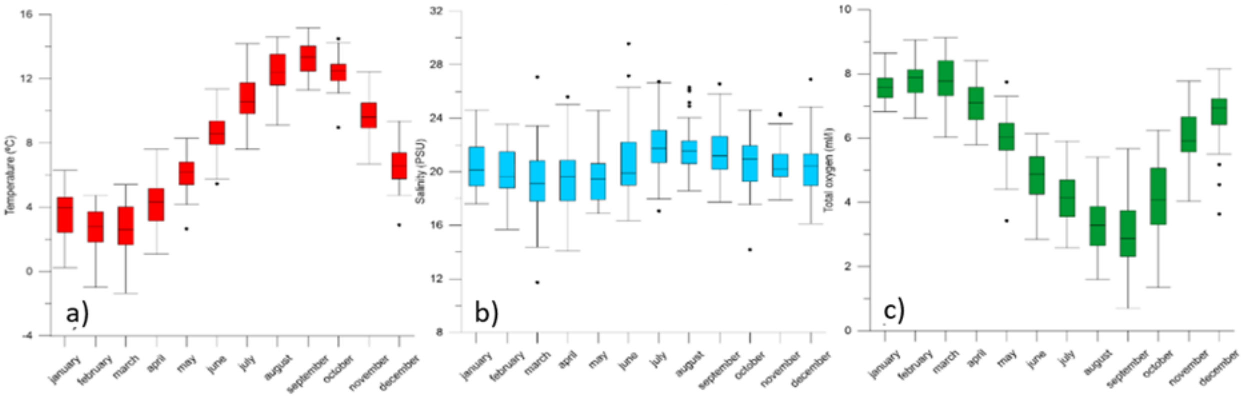

Figure 8. The modern hydrographic settings for Ristinge shows the seasonal variability between 1949 and 2019. The graph a-c represents temperature (ºC), salinity (PSU) and dissolved oxygen concentration (ml/l), respectively. The data was acquired from the Baltic Nest Institute, Stockholm University Baltic Sea Centre, 2020.

4.4 Obrzynowo, the Baltic Proper

SEM plate for Obrzynowo

A plate was composed for the Obrzynowo station (Figure 9) representing the foraminiferal species (*A.*

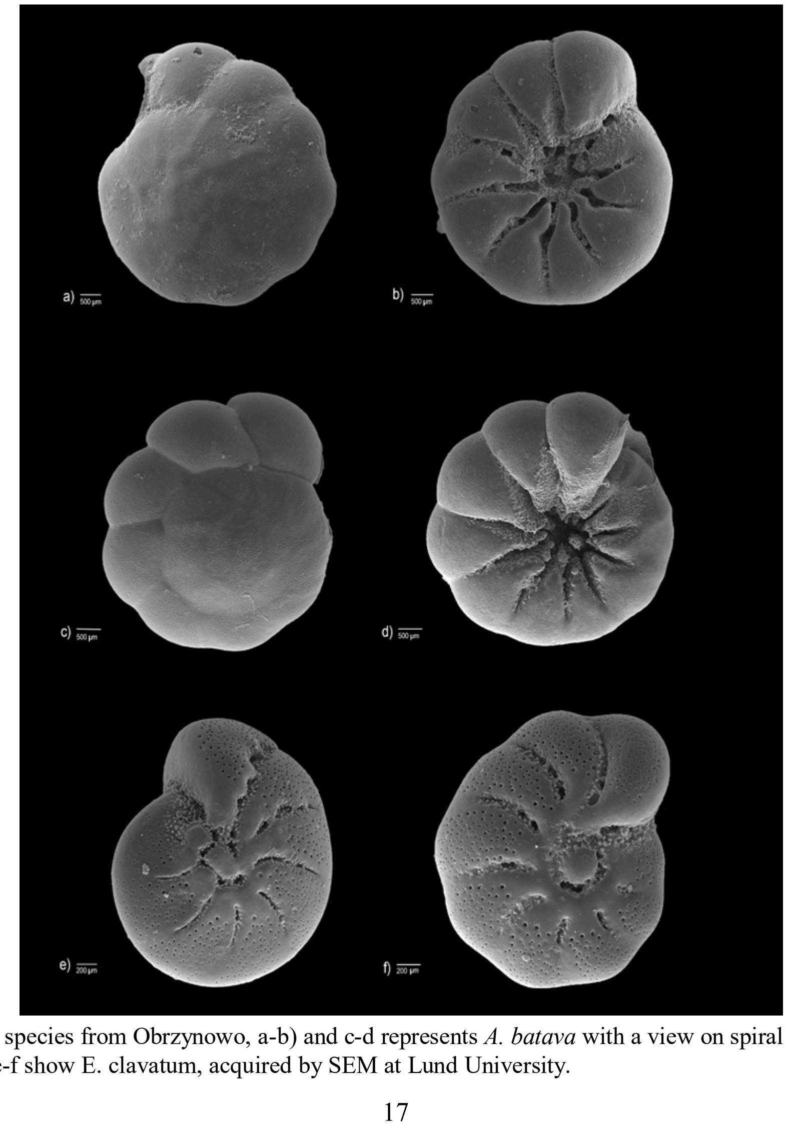

Figure 9: Foraminifera species from Obrzynowo, a-b) and c-d represents *A. batava* with a view on spiral and umbilical side, respectively. Pictures e-f show E. clavatum, acquired by SEM at Lund University.

batava and *E. clavatum*) considered for the trace elemental and the stable isotope analysis.

4.4.1 Trace elemental data

4.4.1.1 Mg/Ca and paleotemperature

The Mg/Ca (Figure 10) samples, ranged between 0.99-1.30 mmol/mol for *A. batava,* and 1.08- 1.56 mmol/mol for *E. clavatum*. One sample was discarded from the analysis in Obrzynowo (E10 at 109.76 cm) because of insufficient amount of material available in the sample.

The temperature reconstruction in Obrzynowo show that the temperatures calculated using *A. batava* ranged between 10.3-15.7ºC with an average of 12.2ºC and for *E. clavatum* 3.6- 6.2ºC with an average of 4.2ºC. No significant trends were recorded. Sample E10 showed a large divergence (with a temperature of 51.43ºC) from the rest of the values and has thus been discarded from the figures but is included in the table. The reason for divergence from other values was probably due to the low Ca concentration, which was below an optimum range for analysis (Table 3, Appendix 1).

4.3.1.2 Ba/Ca and Mn/Ca

The Ba/Ca (Figure 10) ranged between 3.52- 8.55 µmol/mol for *A. batava* and 8.52- 14.11 µmol/mol for *E. clavatum*. *Ammonia batava* showed a significantly increasing trend upwards in the succession, although a decrease is noted in the topmost section.

The Mn/Ca (Figure 10) ranged between, 0.17-0.32 mmol/mol for *A. batava* and 0.10- 0.19 mmol/mol for *E. clavatum*, with no significant trend for this element. The data from the two species are in close range of each other.

4.4.2 Stable oxygen and carbon isotope

The results of the stable isotope measurements of oxygen and carbon for the two species at the Obrzynowo site is presented in figure 10. Data was successfully generated from 60 samples. The range for $\delta^{13}C$ was between -0.79‰ to -3.36‰ for *A. batava*, whereas the range for *E. clavatum* was -1.45‰ to -4.13‰. No significant trends were recorded for $\delta^{13}C$. For the oxygen isotope, $\delta^{18}O$, the range was -4.55‰ to -5.93‰ for *A. batava* and -1.91‰ to -3.71‰ for *E. clavatum* that has a significantly negative trend (Table 3, Appendix 2).

4.4.3 Modern hydrography in Obrzynowo

The modern hydrographic settings Obrzynowo area is shown in figure 11. The data was from 30.1 m water depth, which closely corresponded to the assumed water depth during the Eemian at this location. The temperatures ranged between 2.2 to 12.2ºC throughout the year, with a lower temperature average (~7.3ºC) in the autumn-winter months than in the spring-summer (~5.8ºC). The salinity was substantially analogous, staying within the range of 7.5- 7.7. The dissolved oxygen [O_2] ranged from 6.7 to 9.3 ml/l and displayed the opposite to temperature fluctuations throughout the year, and with a smaller amplitude. Although a seasonal pattern can be seen in the oxygen levels, the bottom shows well-oxygenated conditions.

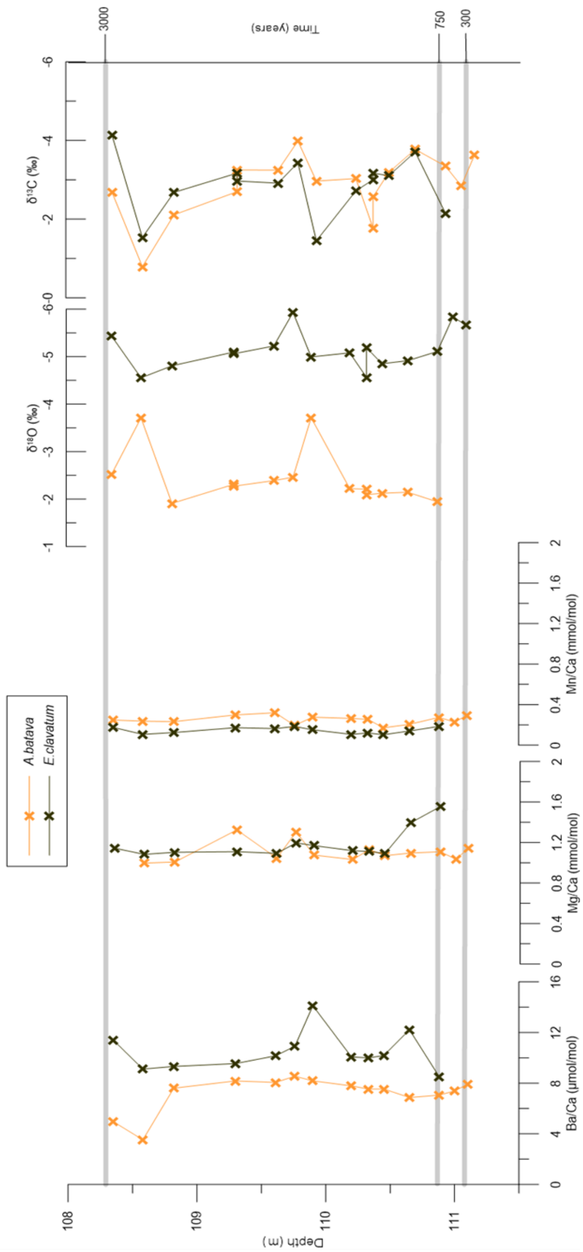

Figure 10. This figure represents trace element and isotopes measurements for Obrzynowo. The elements presented in the figure are Ba/Ca, Mg/Ca, and Mn/Ca. The timescale follows Knudsen et al. (2011), years after the commence of the Eemian. The oxygen and carbon isotopes values from Obrzynowo show values for *A. batava* and E. clavatum.

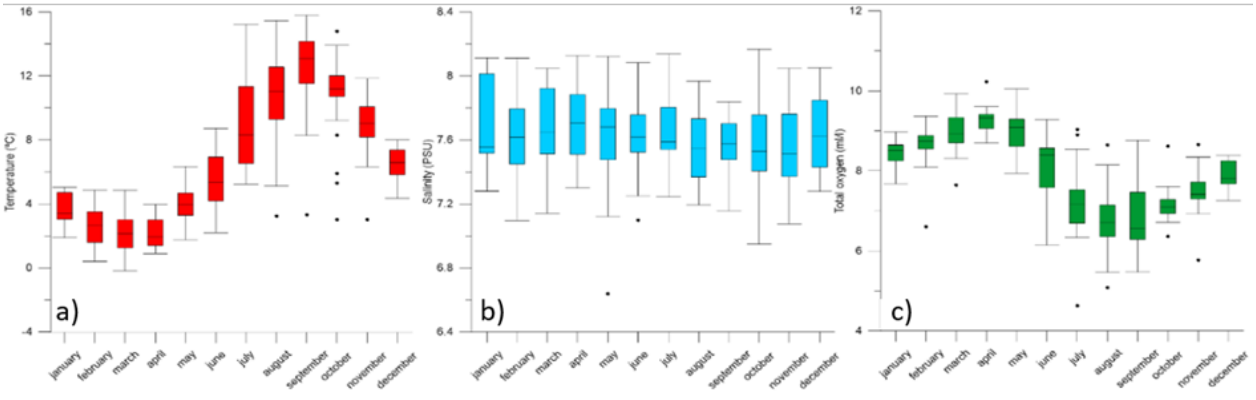

Figure 11. The modern hydrographic settings for Obrzynowo demonstrating the seasonal variability. The graph a-c represents temperature (ºC), salinity (PSU) and dissolved oxygen concentration (ml/l), respectively. The data from 1949 and 2019 were acquired from the Baltic Nest Institute, Stockholm University Baltic Sea Centre, 2020.

5 Discussion

Here the multi-proxy approach with trace elemental and stable isotopic trends are discussed, the outline follows that of the results and includes all three stations. The data (see results) is also discussed with consideration to the modern hydrographic measurements to yield a possible seasonal connection to the geochemistry shown by the foraminiferal analysis. Moreover, the understanding of foraminiferal specific environmental requirements gives an insight into the interpretations.

The results were assessed with the underlying assumptions following the temperature calibration that were developed using recent foraminiferal core-top data. The results are quantitative and based on species-specific calibrations except for *E. clavatum,* where a species-specific equation is lacking, and the data should be regarded as semi-quantitative. The data is based on benthic foraminifera which represents the bottom-water environment and the reconstructed Eemian sea-level at the locations of the stations (Table 1).

Table 4. The values represent a comparison of trace element ratios (/Ca) for Ba, Mg and Mn from the result section and comparable modern trace element values (average) from Groeneveld et al. (2018) per species for the salinity gradient of present Kattegat to the more brackish environment in Hanö Bay (Baltic), and a corresponding temperature of 9.6ºC and 5.0ºC respectively. The *H. balthica* data was acquired from Rosenthal et al. (2011), in an average temperature of 12.4ºC, based on data from N.E. Atlantic. The table also includes the modern hydrographic temperature range from Baltic Nest, for spring-summer months. The average of values is displayed in parentheses.

Geographical area	Species	Ba/Ca (µmol/mol)	Mg/Ca (mmol/mol)	Mn/Ca (mmol/mol)	Calculated temperatures (ºC)	Modern hydrographic data spring temp. (ºC) Baltic Nest
Anholt	***B. marginata***	0.93-3.93 (2.06)	1.67-2.07 (1.88)	0.063-0.10 (0.085)	6.4-9.9ºC (8.2)	5.4-13.3 (8.9)
	H. balthica	5.35-10.24 (7.59)	3.81-4.53 (4.11)	0.35-0.66 (0.49)	7.9-9.3 (8.5)	
Ristinge	***A. batava***	4.77-18.55 (7.82)	0.36-1.23 (0.91)	0.23-0.45 (0.33)	4.0-12.7 (8.9)	2.63-12.43 (6.3)
	E. clavatum	6.70-19.04 (8.93)	0.93-1.25 (1.17)	0.08-0.24 (0.15)	2.4-7.1 (4.1)	
Obrzynowo	***A. batava***	3.52-8.55 (7.22)	0.99-1.30 (1.11)	0.17-0.32 (0.25)	10.3-15.7 (12.2)	2.15-10.82 (5.8)
	E. clavatum	8.52-14.11 (10.46)	1.08-1.56 (1.18)	0.10-0.1 (0.14)	3.6-6.2 (4.2)	
N.E. Atlantic Rosenthal et al. (2011)	***H. balthica***	-	5.75	-		
Kattegat (modern) Groeneveld et al. (2018)	***A. batava***	(3.45)	(0.94)	(0.079)		
	E. clavatum	(2.80)	(1.01)	(0.036)		
	B. marginata	(1.97)	(1.71)	(0.023)		
Hanö Bay (modern) Groeneveld et al. (2018)	***A. Batava***	(6.8) (*Ammonia T6*)	(0.82) (*Ammonia T6*)	(0.27) (*Ammonia T6*)		
	E. clavatum	(11.4)	(0.79)	(0.88)		

In addition to the instrumental hydrographic measurements from the Baltic Nest (see section 3.6), modern proxy values have been collected from published studies (Table 4) for the corresponding species. The modern values of trace elements (Table 4) acquired from Groeneveld et al. (2018) are later compared to Anholt presented in figure 5 an Obrzynowo in figure 10.

5.1 Trace elemental analysis in Anholt

5.1.1 Mg/Ca and bottom-water reconstruction

The temperature in Anholt 300 years after the Eemian interglacial began (correlated with Danish stations) lies in a similar range of temperatures compared to modern-day values for the spring season. Albeit the temperatures differ from the average hydrographic measurements with -0.2ºC for *B. marginata* and + 0.1ºC for *H.* balthica, it can be seen as an offset to the other ways similar temperatures when compared to the instrumental data from the present.

The reconstructed BWT in the Eemian can be compared to the previous estimation of a 2-3ºC (non-quantitative temperature) higher temperature than in the modern-day, coupled with the rising water level (Seidenkrantz 1993a; Seidenkrantz & Knudsen 1994). Here the results are quantitative and would then coincide with the spring season of the foraminiferal growth as the temperatures are closely comparable to that of the modern-day hydrography (with ±0.1ºC offsets). Another aspect worth considering is the salinity steering of the incorporation of Mg/Ca in certain species, as Groeneveld et al. (2018) conclude the *B. marginata* to be a species dependent on salinity when incorporating Mg/Ca.

5.1.2 Ba/Ca

There is a minor variation of Ba/Ca throughout the time. At the beginning of the Eemian, *B. marginata* displays a slightly increasing trend. *Hyalinea balthica* does not display any trends, but both of the curves seem to have a negative pattern in the initial stage of the interglacial, with a noted decrease of Ba ratio, meaning an increase in salinity. The general trend for *B. marginata* is positive, implying that the salinity throughout the core was decreasing. Coupled with stable oxygen isotopes data from Anholt, note an increasing trend in $\delta^{18}O$, and suggest an increasing salinity (Table 1, Figure 13a). The Kattegat is the main inflow of marine water into the Baltic and is therefore not indicative of changes in salinity, as the other stations further into the estuarine system might be (Groeneveld et al. 2018). The opposite implication of decreasing salinity is therefore not as strong for the Kattegat when measuring the Ba/Ca ratio as it would be in the other stations. The initial pattern of indicated salinity can be compared to similar characteristics in the deepest part of Ristinge record.

5.1.3 Mn/Ca

The Mn/Ca measurements show no significant trends, and the Mn/Ca is relatively small. In comparison to the modern-day values of the same species and similar salinity gradient (Table 4), the ratios of the Mn/Ca in *B. marginata* are substantially higher, almost double albeit still small in contrast to the modern-day measurements of the element in the Kattegat. This can indicate that the oxygen conditions were lower during the Eemian than they are today. The foraminiferal assemblages were increasingly growing in abundance for *B. marginata*, which was also connected to the increased water level or worsened oxygen conditions (Figure 13a) (Seidenkrantz 1993a; Seidenkrantz & Knudsen 1994). Groeneveld & Filipsson (2013) discussed the low ratio of Mn/Ca in the foraminiferal tests of shallow infaunal species (*B. marginata*), as an indication of well-oxygenated water. However, *B. marginata* has also been recognised for being an oxygen depletion tolerant species (Gustafsson & Nordberg 2000). The higher ratios from the Eemian interglacial could, therefore, suggest a more severe oxygen depletion. The $\delta^{13}C$ also showed a significant decreasing trend (Fig. 13a), implying that the bottom water became more stagnant (Ni et al. 2020). The higher values of *H. balthica* can be explained by the higher trace elemental sensitivity as opposed to *B. marginata* (Rosenthal et al. 2011). Even though the *H. balthica* species lacks a significant trend, the values remain higher than those from modern measurements (Table 4) which might indicate a lower oxygen content in the bottom waters of Anholt during the Eemian.

The oscillations that *H. balthica* displayed can indicate an increase in oxygen depletion in a reoccurring manner, possibly due to seasonality. The seasonality albeit small and with marginal fluctuations is present in Anholt in the modern hydrographic data and is similar to the reconstructed temperatures. The cores from Anholt represent the entire Eemian, albeit, at a lower resolution than at the other two sites, this must be taken into consideration when discussing the Anholt sequence.

5.2 Eemian reconstruction in Anholt when coupled with other data

The species investigated are typically from warmer environments, which have been the dominating assemblage in the succession (Seidenkrantz 1993a; Seidenkrantz & Knudsen 1994). The beginning of the record in Anholt (~130- 129 ka B.P.), is represented by an increasing the foraminiferal abundance, concluded by Seidenkrantz (1993a) to have been a transition zone from glacial conditions into a warmer interglacial, with a substantial sea-level rise until reaching 100m water depth further along with the Eemian sediments (Seidenkrantz 1993a). The continuation of the core displays a continuous thriving of the two species (*B. marginata* and *H. balthica*) and an apparent disappearance of the *E. clavatum* species that are discussed in the two other stations (~124 ka B.P.). The upper part of the section in Anholt is distinguished furtherly increased abundance of the species, which can be connected to the decreasing $\delta^{13}C$ and by higher nutrition or decreased amount of dissolved oxygen (Seidenkrantz 1993a and references within).

5.3 Trace elemental analysis in Ristinge

5.3.1 Mg/Ca and bottom-water reconstruction

In comparison to the average BWT from modern hydrographic data, *A. batava* displays a higher temperature during the Eemian than in the present spring-summer temperatures by 2.5º (Table 3). *Elphidium clavatum* does not show similar results as the average temperature of the species during the Eemian, and it is lower than that of the modern data. Albeit the temperature resulted in being lower for this species, Mg/Ca for *E. clavatum* shows a higher ratio of incorporated Mg in the Eemian, than it does in modern foraminiferal samples (Table 4). This could possibly be due to the semi-quantitative results for *E. clavatum.* The difference between the two species could also be a result of growth during different times of the year.

5.3.2 Ba/Ca

The decreasing Ba/Ca trend of *A. batava* is especially pronounced in the lowest (older) part of the section, before c. 750 years after the beginning of the Eemian, it is continuous throughout the section (Figure 13b). This suggests a rapid increase of the salinity in the initial part of the section and then a less dramatic but still prevailing marine input. This is further supported by the stable oxygen isotopes data that show enrichment of the heavy oxygen isotopes with time, seen in the $\delta^{18}O$ trends of both species from Ristinge. This initial increase in salinity can be correlated with an increasing sea level which is connected to the opening of the Danish straits and a continuous sea-level rise (Knudsen et al. 2011).

5.3.3 Mn/Ca

The proxy data in Ristinge displayed no significant trends, but the values can be compared to modern-day ratios (Table 4) showing similarity to the *Ammonia T6* from Hanö Bay. The modern values for *E. clavatum*, on the other hand, are almost four times larger than the measured concentration of Mn/Ca in my samples although the bolstered stratification of the water column could bring lower oxygen levels the faunal diversity. In addition the increase in $\delta^{13}C$ indicated ventilated waters during the Eemian (Figure 13b), probably due to the increased inflow from the Atlantic (Knudsen et al. 2011).

5.4 Eemian reconstruction in Ristinge when coupled with other data

The relative abundance of *A. batava* decreased with time which has been linked to the species-specific worsened vital effect. The abundance of *E.* clavatum, initially low, increased in concentrations (Kristensen et al. 2000) after 750 years until it started to diminish again at approximately 3000 years after the beginning of the Eemian (Figure 13b). The initially high abundance of the *A. batava* have prevailed at the beginning of the Eemian which has been assessed as a brackish environment with increasing salinity later in time. The increase in salinity was also strengthened by the positive trend of the oxygen isotopes at the beginning of this section. The latter change in the faunal assemblage is assigned to the increase in temperature around 750 years after the Eemian. The salinity and temperature were assumed to have stabilised in the middle part of the section, corresponding to after c. 750 years after the Eemian. Following the stable levels, the salinity has yet again begun to rise towards 3000 years after the Eemian with a development of a stronger stratification. The increased salinity at the end of the record was caused by a probably aggravated inflow from the Atlantic, as mentioned before, also indicating that Ristinge was relatively ventilated (Knudsen et al. 2011).

5.5 Trace elemental analysis in Obrzynowo

5.5.1 Mg/Ca and bottom-water reconstruction

The reconstructed BWT (Figure 13c) in Obrzynowo based on *A. batava* Mg/Ca is higher than the modern values showing a 0.29 mmol/mol difference and 0.39 mmol/mol for *E.* clavata when compared (Table 4). A parallel reading for *A. batava* was done with the hydrographic data from the modern-day, and the average temperatures are fairly coinciding when comparing it with the modern trace elemental data (Table 3). The *E. clavatum* is displaying a lower temperature than in the modern spring- summer season, which contradicts previous assumptions of temperature being higher during the Eemian. This contradiction could, similarly to the Ristinge station, be explained by the different time of growth for different species, and while *A. batava* prefers warmer conditions, *E. clavatum* can calcify in colder conditions. The species-specific vital effect is therefore important to consider when interpreting the results (Katz et al. 2010), hence the importance of comparison with the assemblage, salinity and oxygen indications. Knudsen et al. (2012) conclude similarly to the other stations that Obrzynowo represents a higher temperature and salinity during the Eemian. However, the major increase of salinity and temperature did not affect the Vistula region until after 1100 years, probably due to significant river runoff.

5.5.2 Ba/Ca and the Isotope data

Ammonia batava showed an increasing trend for Ba/Ca throughout time (Figure 13c). As mentioned in the previous section, river runoff is a significant factor in the conditions prevailing in the Vistula area (Knudsen et al. 2012). To complement this trend, there was a recorded negative trend of $\delta^{18}O$ for *E. clavatum*, that shows a decrease in salinity as opposed to the trends from the other stations. This might be supported by the influence of freshwater input from the Vistula, also depicted in the growing Ba levels. In contrast to modern trace elemental values (Table 4), the Ba ratio in Obrzynowo during the Eemian was lower. The lower values of Ba/Ca than can be explained by the overall higher salinity due to the increase in marine input from the Atlantic (Knudsen et al. 2012). Although since the results did not show a distinctive increase in salinity, there was probably still a substantial input from of freshwater which consequently attributed to a stronger stratification of the water columns, as the *E. clavatum* prevails as well.

5.5.3 Mn/Ca

The comparison of measured Mn/Ca values and recent foraminiferal studies (Table 4) implies that the reconstructed ratio of incorporated Mn in *A. batava* is slightly lower in contrast to measurements from the Baltic proper (Hanö Bay) for *A batava.* For *E. clavatum*, the values differ greatly, with almost a six times larger divergence, with the lower ration being shown by the Obrzynowo site. There is no significant trend for the carbon isotopes to indicate any apparent trends in changes of the oxygen levels.

5.6 Eemian reconstruction in Obrzynowo when coupled with other data

Foraminiferal assemblage data were available (Table 1), and both species were initially, relatively abundant but later fluctuating. At the end of the record *E. clavatum* drastically declined while the assemblage for *A. batava* began to display a higher concentration. According to the paleoenvironmental reconstruction of Knudsen et al. (2012), the environment in the initial stage of the Eemian was brackish waters and where the salinity decreased furtherly, which could coincide with the fall of the abundance for *A. batava* and later also of the *E. clavatum*. This fall in the abundance can also coincide with the temperature pattern of the *E. clavatum* for that period in the record. The assemblages return to higher values when the salinity increases to the brackish environment continuously throughout the rest of the section.

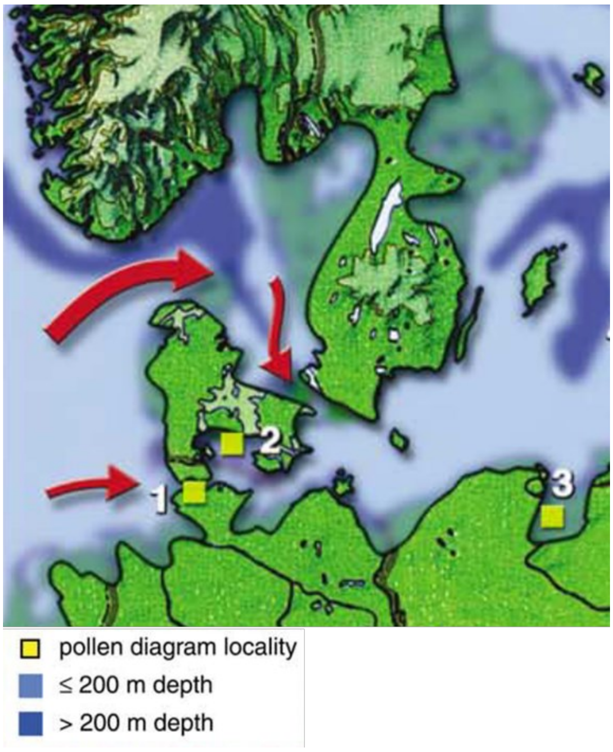

Figure 12. The figure depicts the hydrography during the Eemian early stages including the main inflow routes. The figure has been modified from Funder et al. 2002 and references within.

5.7 An overview of the Eemian hydrography and conditions

The hydrography of the Eemian Baltic area has certain similarities but also some differences to the modern settings, which can be coupled with the results to used as a base for the interpretations of the past conditions. The restrictive passages into the Baltic were broader than the present as well as smaller connections to the North Sea were established, due to inundation with the transgression and eustatic effects (Knudsen 1994; Funder et al. 2002). The main passage from the North Sea through the Kattegat was possibly transversing the Danish straits to a vaster extent than in the Holocene (Figure 12). Previous studies show that the transition area into the Baltic sea was much broader and stronger currents persisted in the circulation, as shown by marine evidence from that area (Lykke-Andersen et al. 1993; Seidenkrantz 1993a; Funder et al. 2002) and strengthened by the results of this thesis. n addition to the extensive water exchange through the Straits, a possible passage from the North Sea into the Baltic was also present between the present northern coast of Germany and southern Denmark (Kiel Canal). The marine connection between the Baltic and the North Sea influenced the salinity in the western Baltic area (e.g. Björck et al. 2000; Seidenkrantz et al. 2000). However, the inflow seems to have been marginal (Funder et al. 2002). In the later Eemian a sea-level drop is noted in geological records, with weakened currents and consequently less water exchange between the northern sea and the Baltic (Knudsen 1994; Seidenkrantz & Knudsen 1994).

To complete the hydrography of the Eemian, the multiproxy correlation of the data from the three sites resulted in absolute temperatures (tentative for *E. clavatum*) that indicate generally warmer bottom water conditions during the Eemian in the Baltic but not in Anholt. The salinity is correspondingly increasing throughout the record indicating the beginning of the Eemian, and it is essential to note that the three stations correspond to different time lengths, placing Ristinge and Obrzynowo as only part of the record in Anholt which has a broader resolution (time correlation in Figure 13). The three sites have been correlated using the measurements, older studies, and modern analogues. The foraminiferal data presented is based on benthic foraminifera hence the assumption that the results will be representative for the conditions in bottom water environments (Katz et al. 2010).

The measurements from the Anholt station cover a considerably longer time range but at a lower resolution than the other two stations, which is displayed in the correlation between the three stations (Figure 13). The reconstructed temperatures have been presented on a common timescale, and their differences can be seen from species to species. The offset observed between species like *A. batava* and *E. clavatum* might indicate a seasonal variability, the different species grow during different parts of the year (Murray 2006; Andersen et al. 2009). The modern hydrographic data displayed a considerable seasonal variability and can here be coupled with the offsets of species-specific reconstructions.

The approach on seasonal calcification of different species has previously been discussed in a number of studies (e.g. Filipsson et al. 2004; Kristjánsdóttir et al. 2007; Toyofuku et al. 2011; Skirbekk et al.

2016; Barrientos et al. 2018) where the importance of the time of calcification is highlighted. The most suitable conditions for a foraminiferal species differ, which results in higher growth rates during the different seasons. The most notable discrepancy in the results is being shown by *A. batava* and *E. clavatum*. *Ammonia batava* is an opportunistic species but with a preference to calcify in relatively warm water (Knudsen et al. 2011; Toyofuku et al. 2011). *Elphidium clavatum* being a cool water species implies its preference to calcify its tests to be in the colder season (Barrientos et al. 2018). Although, a driving force when calcifying the shells in colder temperatures could also have been the nutrient enrichment during the colder periods of the season (e.g. Gustafsson & Nordberg 2000; Murray 2006). Hence, the seasonally calcifying foraminifera can result in a biased temperature reconstruction (Kristjánsdóttir et al. 2007), which is essential to keep in mind when interpreting quantitative data. Barrientos et al. (2018) conclude that seasonality has an impact on waters shallower than 200 m depth in the Arctic. An important connection between test calcification and seasonality in shallower water depths are also highlighted by Groeneveld et al. (2018) with the example of Anholt.

The use of a pollen stratigraphy correlation also strengthens the water inflow argument during that time, implying that the water level started to rise before c.650 years after the Eemian began (Kristensen et al. 2000; Knudsen et al. 2011). Kristensen et al. (2000) and Seidenkrantz et al. (2000) also argue that the fully marine conditions were not established until after 3000 years since the beginning of the Eemian. This is supported by the increasingly marine conditions in both Ristinge and Obrzynowo after 750 years after the Eemian until the end of the section which fell around 3000 years after the Eemian. However, Obrzynowo remains with brackish conditions, albeit the marine transgression into the Baltic. In comparison with modern hydrographic settings, the salinity was higher during the high stand of the Eemian than in the present times (Kristensen et al. 2000; Seidenkrantz et al. 2000). Seidenkrantz et al. (2000) also pointed out that locations in the more western regions, beyond Ristinge, had established more saline conditions before the eastern parts. The higher saline conditions could also have support in the possible direct connection with marine influence directly into the western Baltic from the North Sea (Seidenkrantz et al. 2000). The discrepancy in development between Obrzynowo and the other stations is also indicated by the higher Ba concentrations in Obrzynowo complemented by the negative trend in $\delta^{18}O$ that implies a decrease in salinity, as opposed to the increase of salinity for Anholt and Ristinge. The most plausible cause for the prevailing lower salinities can be interpreted as substantial freshwater input from the Vistula influence (Knudsen et al. 2012). To summarise, this enables an attempt to place the three stations over a salinity gradient, leading from the marine environments in Kattegat (Anholt) to increasingly brackish trough Danish straits (Ristinge) to the Lower Vistula area (Obrzynowo). The Eemian indication is also supported by the enclosed environments having a stronger relationship between salinity and Ba/Ca as the element originated from land river runoff (Groeneveld et al. 2018).

The uptake difference of the Ba element by the calcifying shells is small in-between species (Lea 1999). The results of Ristinge and Obrzynowo display a small difference when it comes Ba/Ca, yet in Anholt a vaster difference can be noted. It is believed that the Ba concentrations in the bottom waters were higher during glacial conditions (Lea 1999). However, the Ba/Ca concentrations might show a connection with salinity as it is related to the land runoff, also shown in the measurements coming from the Kattegat, which has a direct connection to the open marine environments (Skagerrak and the North Sea) (Groeneveld et al. 2018).

The Eemian records compiled in Funder & Balic-Zunic (2006) and references therein describe the Ristinge area to have had more ventilation (Atlantic input trough Danish straits) as opposed to that indicated by the Cyprina Clay in Mommark (Danish straits) that indicates low oxygen conditions (Kristensen et al. 2000; Funder & Balic-Zunic 2006). Ristinge is believed to have been well ventilated during the sea-level increase, which coincides with the results. That characteristic subsided later in the Eemian (Funder & Balic-Zunic 2006), which does not have support in results from this thesis as the Ristinge secession only covers the beginning to the mid-Eemian.

Considering using different species as proxies it is important to note the species habitual preference of sediment depth might be misleading, due to oxygen levels decreasing deeper into the sediment and would hence derive higher Mn/Ca in the tests (Groeneveld & Filipsson 2013; Groeneveld et al. 2018). The foraminifera used for measurements have been cleaned with procedures presented in methods and the typical value after a cleansing treatment is less than 0.1 mmol/mol (Barker et al. 2003; Groeneveld & Filipsson 2013). The data has not been converted into quantitative units of dissolved oxygen concentration. However, the Mn/Ca implies a potential pattern and is compared to the measurements from the present (Table 4). The isotopic record in Knudsen et al. (2011) shows increasing oxygen and carbon isotopes in *A. batava.* With time, the faunal assemblage increases in abundance, reflecting the change from a shallow brackish environment to deeper water towards 3000 years after the Eemian began. The increase of water level probably strengthened the stratification, and this is also suggested by the *E. clavatum* oxygen isotopes records in Knudsen et al. (2011). The carbon isotopes follow the increase, yet the bottom water conditions in Ristinge were fairly oxygenated. The abundance of *B. marginata* in Anholt, after the initiation of the interglacial with other species, can also be indicative of lowering oxygen concentrations in the bottom waters due to raised water levels (Seidenkrantz 1993a; Seidenkrantz & Knudsen 1994) in the less ventilated regions of the Baltic. Knudsen et al. (2012) summarise that a late salinity increase at 1100 years occurred in the Vistula region. The connection to that in trace elemental data can possibly be seen in the lower variability in Ba/Ca in comparison the Ristinge with more variable results, although once again, a more plausible explanation is the larger freshwater input from rivers (Vistula). That being said, complies with the position specific characteristics imposed by access to fresh and saline water. The area of Ristinge is more variable due to the connection to fully marine conditions, imposing a more dramatic change of conditions. The Vistula supplies the Obrzynowo area with freshwater to a larger extent in comparison to the other two stations and their freshwater contribution.

Referring to the modern instrumental data corresponding to the assumed bottom water level during the Eemian, there is seasonal steering of the oxygen levels during the year. The impact of seasonality in hypoxia has also been discussed (e.g. Groeneveld & Filipsson 2013; Asteman & Nordberg 2018; Groeneveld et al. 2018) although the reconstructed data does not show any apparent sign of seasonality, *H. balthica* displays reoccurring fluctuations with a higher Mn/Ca, that could possibly be connected to seasons. Considering that different species have different optimal conditions for the growth of the test (Groeneveld et al. 2018), a coupling with foraminiferal assemblage could imply that more organic matter is available. Conditions that prevail abundance of organic matter tend to exhibit a decrease in oxygen levels (Katz et al. 2010). Groeneveld et al. (2018) provide one of a possible explanation for low Mn ratio in foraminiferal shells to be calcification of test during a more oxygenated time of the year, for example in the Kattegat during spring. A suggestion for a reason for the lack of significant trends in some cases might be connected to some limitations that arise when reconstructing past environments from trace elemental and isotopic data (Hönisch 2002).

5.8 Future analogue implication

As the temperatures during the Eemian were higher than in the present in a number of the results were in accordance to previous paleo indications of the interglacial period (e.g. Funder et al. 2002; Knudsen et al. 2011) a possible correlation between temperature depletion of oxygen levels can be made for a future analogue. An increased risk for low oxygen levels (hypoxic to anoxic conditions) can become a more widespread phenomenon than it is today due to climate change (Diaz & Rosenberg 2008; Conley et al. 2009). In recent studies (e.g. Diaz & Rosenberg 2008; Conley et al. 2009; Conley et al. 2011; Asteman & Nordberg 2018; Charrieau et al. 2018) it has been discussed that the increase of such hydrographic characteristics have prevailed in the latest years and they might continue to develop.

As concluded in the previous sections, the environmental characteristics from the Eemian interglacial were displaying signs of higher water temperature as well as oxygen-poor conditions and strong stratification. As inferred by Groeneveld & Filipsson (2013), the ongoing climate change is having an effect on these characteristics. Therefore, to understand the development of the climate in the future the past should be better understood.

The paleoclimatic reconstruction can, in a broader sense serve as a reference to the dynamics of an interglacial period and can be implemented to be helpful in modelling and climatic predictions (Plikk et al. 2019).

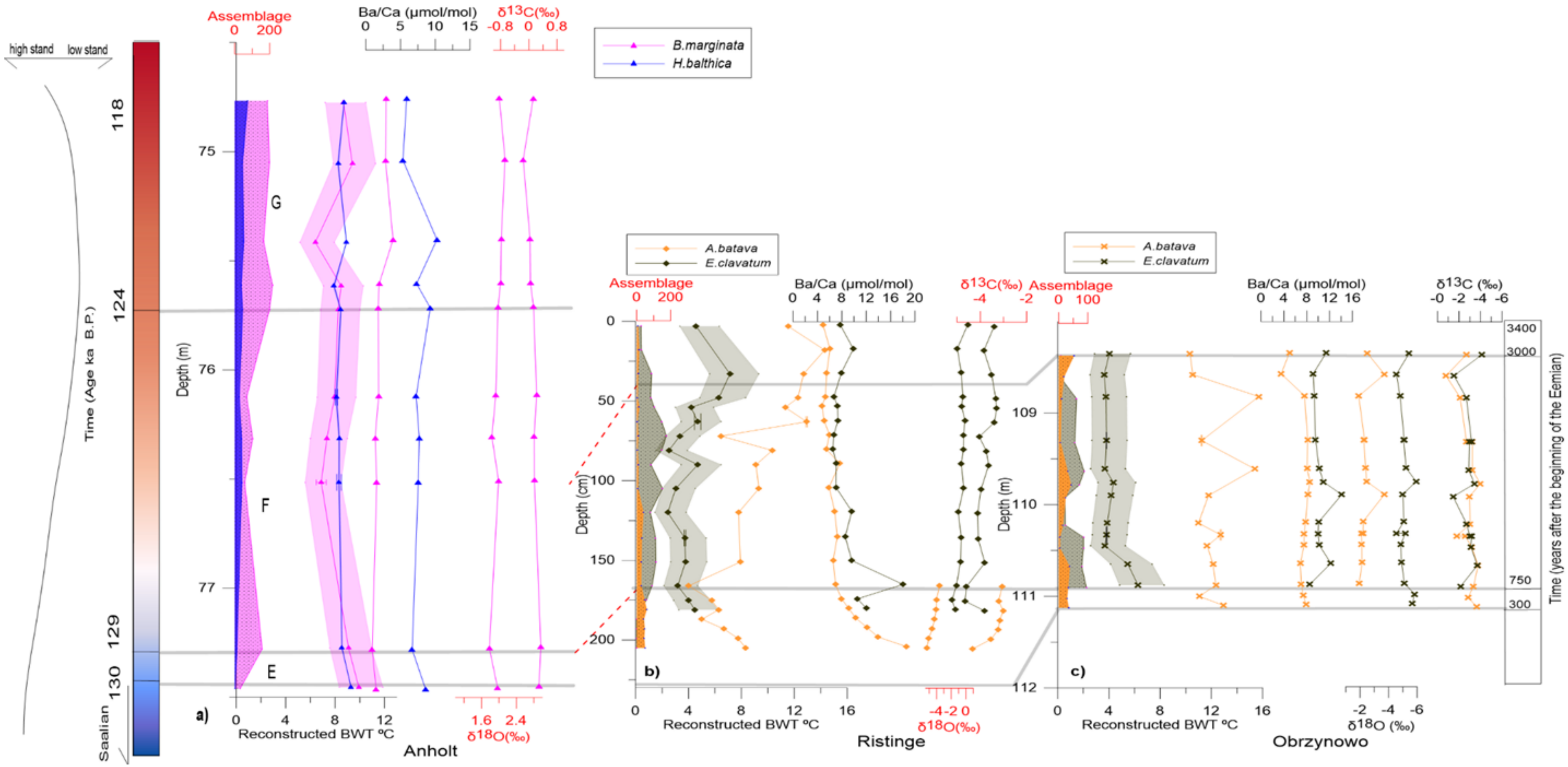

Figure 13. A summary plot represents trace elemental data and isotopic data from measurements conducted in this thesis and additional results from previous studies. Graph a) shows calculated temperatures, Ba/Ca and assemblage data of *B. marginata* and *H. balthica in* Anholt. The isotope data is from Knudsen et. al 2011, for the Bulimina species. Graph b) includes the same parameters as a) but for batava and *E. clavatum* in Ristinge and c) shows parameters for of A. batava and *E. clavatum* resulting from this thesis and assemblage data from Knudsen et al 2012 in Obrzynowo. The data has been plotted according to corresponding depths. The error bars present in the BWT reconstructions illustrate the variation in replicate samples. The error envelope in a), and *E. clavatum* in b) and c) is acquired through the ± variations of the calibrations applied in temperature estimation (Table 2). Obrzynowo is also displays the stable isotope measurements conducted in this thesis. The figure has two partially correlated timelines, one a floating chronology based on (Knudsen et al. 2011; Knudsen et al. 2012) for Ristinge and Obrzynowo in years after the beginning of Eemian, and a stable marine isotope events based timeline after (Martinson et al. 1987; Seidenkrantz 1993a) in Anholt. The correlation based on (Funder et al. 2002; Miettinen et al. 2014) with the original data from the tree stations (see table 1). The sea level curve was roughly estimated after (Miettinen et al. 2014).

6 Conclusions

Here, I present the contribution of proxy data for the paleoclimatic reconstructions of the bottom water conditions from three locations in the Baltic, during the last interglacial. The results show quantitatively reconstructed temperatures for the majority of the data (and semi-quantitaive reconstruction of *E. clavatum*) and other environmental indications interpreted from trace elemental data with accordance to previous studies. The aims of this thesis have been summarised for each location.

- **In Anholt,** the reconstructed bottom temperatures during the Eemian were calculated to 8.2ºC (ranging 6.4-9.9ºC) for *B. marginata* and 8.5ºC (7.9-9.3ºC) for *Hyalinea balthica*. The reconstructed BWT are similar to the modern conditions. The salinity interpretation is more concurrent with previous results, suggesting an increase in salinity with time, during the interglacial, supported by the trace elemental results conducted for this thesis and complementary isotope ($\delta^{18}O$) and assemblage data from previous research. The trace elemental data has less impact on salinity reconstructions than at the other two stations. The oxygen conditions in Anholt were estimated to have been decreasing with the increasing sea level and salinity, this was supported by the decreasing carbon isotopes, as the trace elemental data of Mn do not show significant trends in the record. The values of Mn/Ca are, however, higher than in modern measurements, suggesting a lower ventilation and probable, lower oxygen content. A possible indication of seasonal impact can be seen in Anholt, although the resolution is low and should be considered when interpreting the data.
- **In Ristinge,** the bottom water temperatures for *A. batava*, an average of 8.9ºC (ranging 4.0-12.7ºC) were higher than in the present. Temperature for the semi-quantitative reconstruction of *E. clavatum* of 4.1ºC (ranging 2.4-7.1ºC), shows lower values when compared to the modern conditions, although the trace elemental Mg/Ca is higher. The marine influence during the Eemian is in Ristinge supported by trace elemental indication of increasing salinity, supported by isotopic data. The ventilation of the site was presumed good during the interglacial period, due to the dynamic environment in the Danish straits in comparison to the other sites.
- **In Obrzynowo,** the bottom water temperature resulted in higher than today values for *A. batava* with an average of 12.2ºC (ranging 10.3-15.7ºC), but lower temperature for *E. clavatum* of 4.2ºC (ranging 3.6- 6.2ºC), during the last interglacial. The consensus is that the bottom water temperature in Ristinge was higher, probably due to the different foraminifera species calcifying in different conditions in general, hence recording, e.g. lower temperatures and seasonal growth. Salinity indications resulting from this thesis show a decrease in salinity during the Eemian, connected to the freshwater input from the Vistula river, strengthened by isotopic data and assemblages from previous publications. An interpretation of oxygen conditions for this location is complicated, but the coupling with carbon isotopes might imply a strong stratification and rather oxygen-poor conditions.
- **The reconstruction of the Eemian** can serve as a good analogue for the steadily changing climate and support further research with the proxy for driving factors helpful in modelling and predicting future environments, e.g. the growing low oxygen conditions in the Baltic.

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9 Appendix
Appendix 1:

The result from IOCP analysis.

Depth Anholt	Sample	Species or type	Ba/Ca	Mg/Ca (mmol/mol)	Mn/Ca (mmol/mol)	Temperature (ºC)
74.76-74.79	A1	*B. marginata*	2.942	1.928	0.081	8.680
75.04-75.07	A2	*B. marginata*	2.841	2.009	0.098	9.393
75.40-75.43	A3	*B. marginata*	3.932	1.667	0.101	6.395
75.60-75.63	A4	*B. marginata*	1.930	1.906	0.101	8.490
75.71-75.74	A5	*B. marginata*	1.774	1.878	0.088	8.247
76.11-76.14	A6	*B. marginata*	2.293	1.749	0.080	7.953
76.11-76.14*	A7	*B. marginata*	1.425	1.940	0.072	*
76.30-76.33	A8	*B. marginata*	1.346	1.774	0.074	7.330
76.50-76.53	A9	*B. marginata*	1.922	1.829	0.088	6.874
76.50-76.53*	A10	*B. marginata*	1.259	1.614	0.086	*
77.26-77.29	A11	*B. marginata*	0.928	1.974	0.063	9.087
77.44-77.47	A12	*B. marginata*	1.495	2.069	0.081	9.918
74.76-74.79	B1	*H. balthica*	5.885	4.227	0.556	8.720
75.04-75.07	B2	*H. balthica*	5.349	3.981	0.369	8.247
75.40-75.43	B3	*H. balthica*	10.241	4.328	0.539	8.914
75.60-75.63	B4	*H. balthica*	7.317	3.805	0.557	7.909
75.71-75.74	B5	*H. balthica*	9.289	4.095	0.518	8.465
76.11-76.14	B6	*H. balthica*	7.793	3.811	0.359	8.103
76.11-76.14*	B7	*H. balthica*	6.723	4.002	0.396	*
76.30-76.33	B8	*H. balthica*	7.703	4.028	0.526	1.603
76.50-76.53	B9	*H. balthica*	7.093	3.841	0.627	1.797
76.50-76.53*	B10	*H. balthica*	8.039	4.203	0.686	*
77.26-77.29	B11	*H. balthica*	6.680	4.144	0.427	1.412
77.44-77.47	B12	*H. balthica*	8.615	4.526	0.353	1.269

Depth Ristinge	Sample	Species or type	Ba/Ca (µmol/mol)	Mg/Ca (mmol/mol)	Mn/Ca (mmol/mol)	Temperature (°C)
3	C1	*A. batava*	4.937	1.061	0.225	11.528
18	C2	*A. batava*	6.067	1.230	0.300	14.298
33	C3	*A. batava*	5.531	1.129	0.330	12.694
48	C4	*A. batava*	5.336	1.104	0.238	12.279
54	C5	*A. batava*	4.769	1.049	0.242	11.316
63	C6	*A. batava*	4.932	1.091	0.360	12.054
63	C7	*A. batava*	5.292	1.196	0.308	*
72	C8	*A. batava*	5.977	0.811	0.336	6.465
81	C9	*A. batava*	5.468	0.995	0.334	10.328
90	C10	*A. batava*	7.657	0.933	0.397	9.108
105	C11	*A. batava*	5.915	0.944	0.370	9.320
120	C12	*A. batava*	6.859	0.869	0.354	7.780
136	C13	*A. batava*	7.460	0.902	0.391	7.888
136	C14	*A. batava*	7.083	0.847	0.359	*
151	C15	*A. batava*	6.580	0.876	0.295	7.928
166	C16	*A. batava*	6.982	0.712	0.321	4.015
175	C17	*A. batava*	7.961	0.780	0.413	5.752
181	C18	*A. batava*	9.124	0.803	0.450	6.278
187	C19	*A. batava*	10.251	0.750	0.301	5.010
193	C20	*A. batava*	12.126	0.819	0.296	6.655
199	C21	*A. batava*	13.910	0.868	0.380	7.749
205	C22	*A. batava*	18.549	0.895	0.240	8.322
3	D1	*E. clavatum*	7.763	1.230	0.218	4.566
18	D2	*E. clavatum*	9.892	2.041	0.153	8.264
33	D3	*E. clavatum*	7.924	1.749	0.144	7.137
48	D4	*E. clavatum*	6.735	1.558	0.097	6.294
54	D5	*E. clavatum*	7.313	1.171	0.188	4.205
63	D6	*E. clavatum*	7.309	1.012	0.218	4.689
63	D7	*E. clavatum*	7.443	1.489	0.174	*
72	D8	*E. clavatum*	6.700	1.039	0.133	3.336
81	D9	*E. clavatum*	6.557	0.929	0.125	2.515
90	D10	*E. clavatum*	7.105	1.253	0.133	4.699
105	D11	*E. clavatum*	7.047	0.997	0.142	3.030
120	D12	*E. clavatum*	9.631	0.918	0.153	2.430
136	D13	*E. clavatum*	7.671	1.027	0.142	3.723
136	D14	*E. clavatum*	9.450	1.165	0.116	*
151	D15	*E. clavatum*	9.649	1.104	0.151	3.776
166	D16	*E. clavatum*	18.041	1.018	0.083	3.188
175	D17	*E. clavatum*	10.575	1.141	0.122	4.017
181	D18	*E. clavatum*	12.009	1.214	0.243	4.470

Depth Obrzynowo	**Sample**	**Species or type**	**Ba/Ca (µmol/mol)**	**Mg/Ca (mmol/mol)**	**Mn/Ca (mmol/mol)**	**Temperature (ºC)**
111.1	E1	*A. batava*	7.905	1.144	0.291	12.944
111	E2	*A. batava*	7.380	1.035	0.229	11.053
110.88	E3	*A. batava*	7.051	1.108	0.273	12.345
110.65	E4	*A. batava*	6.860	1.096	0.204	12.132
110.45	E5	*A. batava*	7.536	1.069	0.171	11.675
110.33	E6	*A. batava*	7.643	1.074	0.254	12.727
110,33*	E7	*A. batava*	7.417	1.188	0.254	*
110.2	E8	*A. batava*	7.781	1.031	0.263	10.989
109.9	E9	*A. batava*	8.177	1.075	0.276	11.771
109.76	E10	*A. batava*	8.546	8.863	0.194	51.43
109.61	E11	*A. batava*	8.053	1.303	0.319	15.390
109.3	E12	*A. batava*	7.858	1.073	0.382	11.240
109,3*	E13	*A. batava*	8.484	1.017	0.213	*
108.82	E14	*A. batava*	7.602	1.324	0.231	15.695
108.58	E15	*A. batava*	3.522	1.007	0.237	10.548
108.35	E16	*A. batava*	4.958	0.996	0.247	10.334
110.88	F1	*E. clavatum*	8.518	1.555	0.185	6.2755
110.65	F2	*E. clavatum*	12.216	1.394	0.139	5.4815
110.45	F3	*E. clavatum*	10.174	1.091	0.102	3.6909
110.33	F4	*E. clavatum*	9.353	1.081	0.141	3.8208
110,33*	F5	*E. clavatum*	10.638	1.140	0.098	*
110.2	F6	*E. clavatum*	10.064	1.119	0.106	3.8733
109.9	F7	*E. clavatum*	14.114	1.169	0.151	4.1926
109.76	F8	*E. clavatum*	10.907	1.196	0.184	4.3596
109.61	F9	*E. clavatum*	10.155	1.093	0.163	3.7033
109.3	F10	*E. clavatum*	9.547	1.121	0.149	3.8076
109,3*	F11	*E. clavatum*	9.543	1.096	0.194	*
108.82	F12	*E. clavatum*	9.315	1.103	0.124	3.7720
108.58	F13	*E. clavatum*	9.110	1.083	0.106	3.6351
108.35	F14	*E. clavatum*	11.403	1.143	0.175	4.0325

Appendix 2:

This table represents the stable isotopes measurements for Obrzynowo.

Sample ID	Depth	Species or Type	$\delta^{13}C$ VPDB corr	$\delta^{18}O$ VPDB corr
G1	111.1	*Ammonia*	-3.63	-5.67
G2	111	*Ammonia*	-2.85	-5.84
G3	110.88	*Ammonia*	-3.34	-5.11
G4	110.65	*Ammonia*	-3.77	-4.91
G5	110.45	*Ammonia*	-3.19	-4.85
G6	110.33	*Ammonia*	-2.56	-5.19
G7	110.33	*Ammonia*	-1.77	-4.56
G8	110.2	*Ammonia*	-3.03	-5.08
G9	109.9	*Ammonia*	-2.97	-4.99
G10	109.76	*Ammonia*	-3.98	-5.93
G11	109.61	*Ammonia*	-3.25	-5.22
G12	109.3	*Ammonia*	-3.25	-5.06
G13	109.3	*Ammonia*	-2.70	-5.10
G14	108.82	*Ammonia*	-2.11	-4.81
G15	108.58	*Ammonia*	-0.79	-4.55
G16	108.35	*Ammonia*	-2.68	-5.44
H1	110.88	*Elphidium*	-2.14	-1.94
H2	110.65	*Elphidium*	-3.71	-2.14
H3	110.45	*Elphidium*	-3.10	-2.12
H4	110.33	*Elphidium*	-3.17	-2.09
H5	110.33	*Elphidium*	-3.00	-2.21
H6	110.2	*Elphidium*	-2.72	-2.22
H7	109.9	*Elphidium*	-1.45	-3.71
H8	109.76	*Elphidium*	-3.43	-2.46
H9	109.61	*Elphidium*	-2.91	-2.39
H10	109.3	*Elphidium*	-2.97	-2.27
H11	109.3	*Elphidium*	-3.17	-2.31
H12	108.82	*Elphidium*	-2.68	-1.91
H13	108.58	*Elphidium*	-1.53	-3.71
H14	108.35	*Elphidium*	-4.13	-2.51

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